Experimental Evidence of the Directional Components of Cosmic Rays

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Abstract

It is possible to resolve the diurnal variation into two components. The first of these has its maximum at 18^h and corresponds to the particle wind predicted in the theory by ALFVÉN (1954). The amplitude ought to be constant both as a function of geomagnetic activity and as a function of time. The second component has its maximum at 12^h. It represents the sum of the various kinds of radial particle flow, and it ought to display variations indirectly related to geomagnetic activity. A search for experimental evidence of these components is made possible through the determination of the incidental directions of the primary particles by BRUNBERG (1953) and BRUNBERG and DATTNER (1953). An analysis of C.R. measurements from Stockholm, Nagoya, and Huancayo seems to confirm the two components and their expected properties. A very doubtful amplitude change of the 18^h-component during major magnetic storms is not at variance with theory. The Stockholm measurements were treated by SANDSTRÖM (1955) as to geomagnetic effects, those from Nagoya and Huancayo by SEKIDO and KODAMA (1952). A seasonal phase shift reported by the latter for geomagnetically quiet days is compared to measurements in Stockholm. If it exists at all the reported phase shift is evidently due to local effects. Other secular or seasonal phase shifts (ELLIOT and THAMBYAPHILLAI 1953) have not been treated in the present study, as the data did not provide any example of these effects. Several points are open to discussion because of the data's being collected with instruments of widely different properties. Directional counter telescopes offer the most valuable results, if they are designed for a comparatively small aperture and measure in at least two directions.

Introduction

According to a theory by ALFVÉN (1954) the main part of all cosmic radiation originates in the sun. The following arguments suffice as an introduction to the study of available experimental results.

The wellknown daily variation can be resolved into components—(1) the wind of cosmic particles caused by the rotation of the sun overtaking the earth in its orbit and (2) a radial flow of particles from the sun. The latter in its turn consists of two components, one being a general outward diffusion of particles and the other a direct flow of particles inside the corpuscular beams associated with active sunspots and solar flares. Outside the beams there ought to be a particle flow of very low intensity in the opposite direction. These conditions are illustrated by the simple scheme in Fig. 1. The corpuscular flow is very variable (even changing its sign) while the particle wind and the particle diffusion ought to display fairly constant features. It is quite possible, however, that the nonvariable particle wind is disturbed whenever a corpuscular beam sweeps across the earth. BRUNBERG and DATTNER (1954) have shown that the rotating beam can retard as well as accelerate the cosmic ray particles in the space surrounding the sun, the effect extending far beyond the earth's

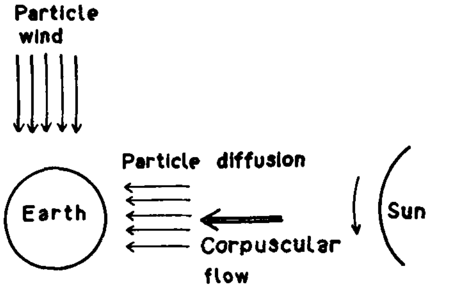

Fig. 1. Simple scheme showing the main components of the cosmic radiation according to Alfvén (1954).

orbit. They have also pointed out that the direct beam will give rise to a 27-day periodicity in case it lasts for a sufficiently long time.

Corrections for the Geomagnetic Field

The directions of the incident particles have to be computed from the time of maximum and the direction of measurement at the point of observation. The correction to be applied to the observed time of maximum corresponds to a simple coordinate transformation in the harmonic dials. It is done by turning the p- and q-axes through an angle which can be read from the experimental curves of Brunberg (1953) and of Brunberg and Dattner (1953). The average momentum of the primary C.R. particles is assumed to be 20GeV/c (Brunberg and Dattner 1954). Fig. 2 illustrates this correction graphically.

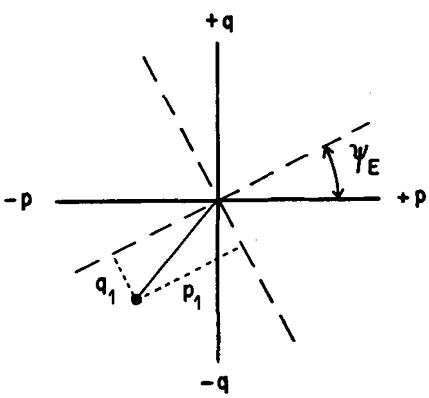

Fig. 2. Graphical correction for the east-west deviation of the C. R. particles in the geomagnetic field.

The Directional Components in the Harmonic Dial

When the geomagnetic effect has been corrected, the new harmonic coefficients p_1 and q_1 represent the two main components discussed in the introduction. The vector p_1 at 18^h evidently represents the wind of C.R. particles, while q_1 at 12^h is the sum of the diffusion of particles and the corpuscular flow (Fig. 3).

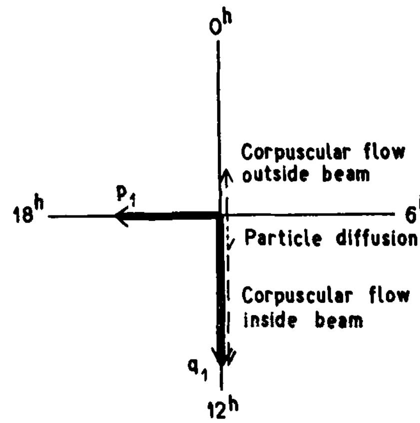

Fig. 3. The vectors representing the components of cosmic radiation.

According to theory we might expect p_1 to be constant under all conditions. During magnetically quiet days q_1 ought to be negligible or positive (equalling the difference between a flow inwards and the diffusion outwards). As already mentioned, disturbances are to be expected. To decrease the influence of the statistical fluctuations it is always necessary to average over a number of days. In this way irregular effects will be diminished or even eliminated if they are of alternating sign.

The secular change of the time of maximum (Elliot and Thambyaphillai 1953, Brunberg 1954) is too large to be accounted for solely by changes in q_1. It is certainly independent of the daily geomagnetic effects (Sandström 1955) and therefore it cannot easily be attributed only to changes in the corpuscular flow.

Measurements from Stockholm

The C.R. data collected in Stockholm by Malmfors (1949) Oct. 1947—June 1950 have

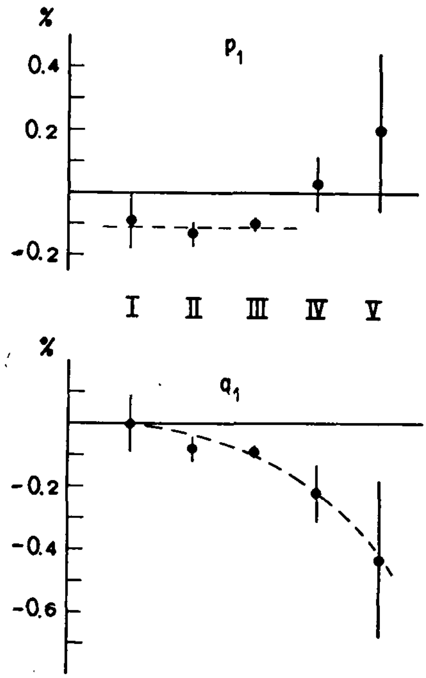

Fig. 4. The 18h-(p_1-) and 12h-(q_1-) components in Stockholm Oct. '49—June '50 in their relation to the maximum K_p-index. The broken line in the upper diagram corresponds to the average of the first three points.

been treated by SANDSTRÖM (1955) as to geomagnetic effects. The days were divided into five groups according to their maximum K_p-indices. Measurements are available in three directions, zenith, 30° to the north, and 30° to the south. After having been corrected for the deviation of the primary particles in the earth's magnetic field the three directions ought to display closely corresponding variations. Accordingly in the present study we employ the averages of all three, thus diminishing the statistical fluctuations by a factor 0.6. The limits of errors will still be very big for the magnetically quiet days comprising class I as well as the most disturbed days comprising class V.

From Fig. 4 we find that p_1 can be regarded as constant for classes I—III, that is the wind of primaries remains constant when the K_p-index increases to 5^+. Contrary to theory p_1 appears to change its sign above this K_p-value. However, when the statistical fluctuations are taken into account, this may be found to be accidental.

It is very interesting to note the changes of q_1. Beyond any doubt the amplitude of the 12^h-component increases with increasing geomagnetic activity. The general trend is consistent with the assumption that this component can be regarded as negligible on magnetically quiet days.

Measurements from Nagoya

SEKIDO and KODAMA (1952) have published a study of the relations between the cosmic ray diurnal variation in Nagoya 1949—51 and the magnetic character figures. After correcting for the deviation of the primaries in the geomagnetic field it is possible to make a comparison between their figure 4 and the data from Stockholm. Instead of the K_p-indices Sekido and Kodama refer their results to the Japanese character figure (J.C.F.) dividing the days into five groups. To diminish the statistical fluctuations they finally work their groups A and B into one. Also the fifth group is wider than the remaining two. Accordingly the groups are not equally spaced. The differences in referring to geomagnetic activity form no serious obstacle in a qualitative comparison with the Stockholm figures.

The Nagoya results with a counter telescope aperture of ± 12° are illustrated in Fig. 5. Evidently the tendency is the same as in the diagrams of Fig. 4. A very prominent difference is the fact that the absolute value of the amplitude is approximately three times that ever recorded in Stockholm. It is also very much bigger than that recorded in Nagoya with apertures of ± 40° and ± 85°. The 18^h- and 12^h-components as measured with these apertures are illustrated in Fig. 6. The harmonic

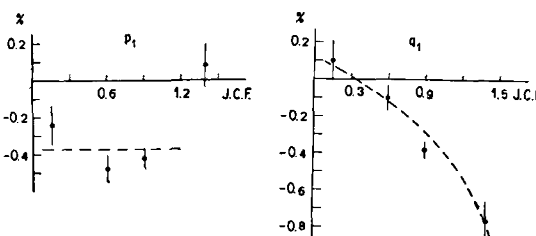

Fig. 5. The 18h-(p_1-) and 12h-(q_1-) components in Nagoya March '49—Sept. '50 in their relation to the Japanese magnetic character figure. Small aperture. The broken line in the upper diagram corresponds to the average of the first three points.

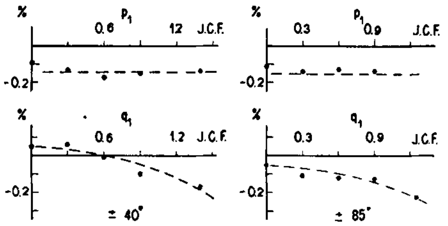

Fig. 6. The 18h-(p_1-) and 12h-(q_1-) components in Nagoya March '49—Sept '50 and Oct. '47—Apr. '49. Large apertures. The broken lines in the two upper diagrams correspond to the averages of the first four points.

coefficients were taken from Fig. 2 in the paper by Sekido and Kodama. In both cases the 18^h-component appears to be constant. In accordance with theory the amplitude of the 12^h-component increases with increasing geomagnetic activity. The discrepancies between the results from telescopes with differing apertures will be treated below.

Measurements from Huancayo

In their paper Sekido and Kodama (1952) have also treated data from Huancayo for the years 1937—45. The position of Huancayo close to the magnetic equator makes it difficult to correct for the deviation of the primaries in the geomagnetic field (compare Brunberg and Dattner 1953, Diagrams 35—37). We must also remenber that the registrations were made by means of an ionization chamber and represent the intensity integrated over the half sphere. If the average momentum of the primaries were assumed to be 20 GeV/c, the angular correction for the deviation in the earth's magnetic field would be 105°. However, the ionization chamber was protected by shields equalling 12 cm of lead, which excluded most of the particles of low energy. It is impossible to predict the actual average value of momentum for the residual radiation. For 25 GeV/c the angular correction is roughly 80°. This has been selected as a first approximation. The harmonic coefficients were taken from Fig. 5 in the paper by Sekido and Kodama (1952). In this case they employed the international character figure C to classify the days geomagnetically. Unfortunately the relation between the C-figures and the K_p-indices is complicated (Howe and Weisman 1949).

The indirect relation of the two main components to geomagnetic activity is shown by Fig. 7. The 18^h-component can be regarded as

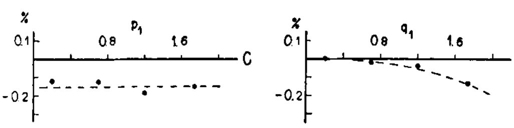

Fig. 7. The two C. R. components as functions of geomagnetic activity. From measurements as Huancayo 1937—'45. The averages have been calculated from the values cited by Sekido and Kodama (1952). The broken line in the upper diagram corresponds to the average of all four points.

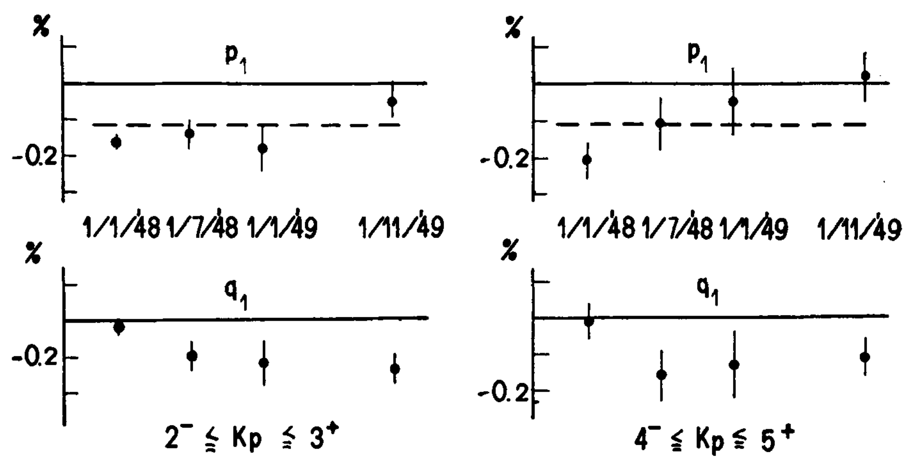

Fig. 8. The 18h-(p_1-) and the 12h-(q_1-) components from the Stockholm measurements versus time for days with a geomagnetic activity characterized by 2— K_p 3+and 4— K_p 5+. The broken line in the upper two diagrams indicates the same average value as the corresponding line in Fig. 4.

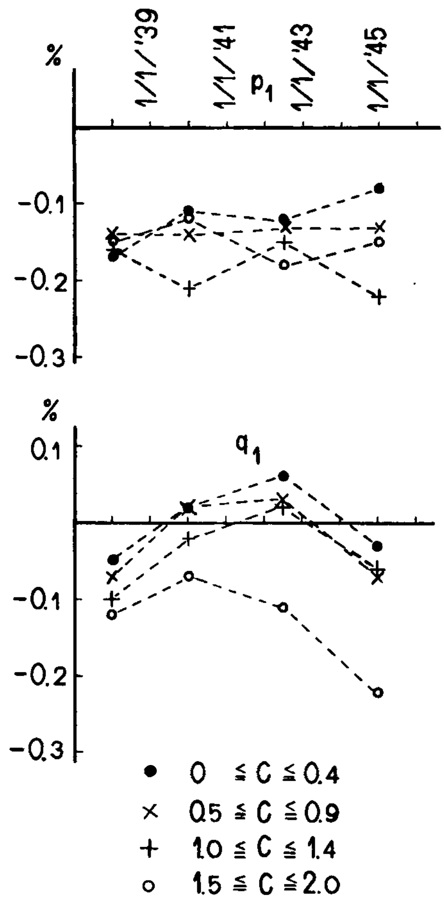

Fig. 9. The 18^h-(p_1-) and 12^h-(q_1-) components from the Huancayo measurements versus time.

constant while the amplitude of the 12^h-component increases with the geomagnetic activity.

Evidently, despite the uncertainty about the correction for the earth's magnetic field, the two components seem to behave in the expected way.

The Components as Functions of Time

The time dependence of the Stockholm measurements can be studied as regards classes II and III only. Days belonging to class I as well as classes IV and V are too few for such a study. Fig. 8 displays the variations of p_1 and q_1 in these cases. The 18^h-components is comparatively constant as regards days of class II but not those of class III. The amplitude of the 18^h-component need not necessarily be constant, as fluctuations, though slight for days belonging to one and the same class (BRUNBERG and DATTNER 1954), are to be expected.

As far as results from Nagoya are concerned, Sekido and Kodama have not published any data suitable for studies of the time dependence. They report only a seasonal change for magnetically quiet days. This will be discussed below.

As regards the registrations from Huancayo, Sekido and Kodama have divided the data into four periods. As they were also sorted in four groups according to geomagnetic activity, we get a good picture of the variations (Fig. 9). The diagram for p_1 does not show any systematic variations, q_1 on the other hand displays a marked systematic variation with the same trend regardless of geomagnetic activity.

Seasonal Variations

There exist observations at variance with theory and also some contradictory experimental results.

A very early time of maximum during spring and summer has repeatedly been reported during the last few years. These reports are confirmed by registrations in three directions in Stockholm (geomagn. lat. 58°) and in Kiruna (geomagn. lat. 68°) during 1954. As no K_p-indices are as yet available for the year 1954 and the number of days is in any case too small for the purpose, no study based on this material of the phase as a function of geomagnetic activity has as yet been made.

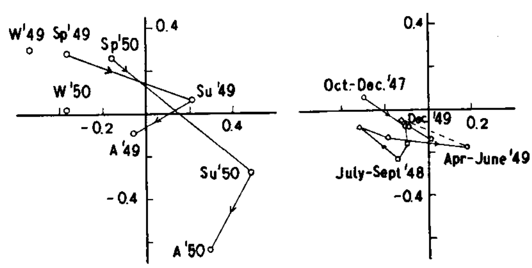

Fig. 10. The seasonal variation of the daily maximum for magnetically quiet days as reported by Sekido and Kodama (to the left) compared to the partly contemporary registrations on magnetically quiet days in Stockholm (to the right). Corrections have been applied for the deviation of the primaries by the earth's magnetic field (compare text).

In their paper SEKIDO and KODAMA (1952) published a harmonic dial demonstrating the variations of the daily maximum from winter (W) through spring (Sp), summer (S), and autumn (A) during 1949 and 1950. When the circles indicating standard deviations have been omitted and the deviation of the primary particles in the earth's magnetic field has been corrected for, the harmonic dial turns into the left diagram of Fig. 10. Only magnetically quiet days are considered ($K_p \leqq 2^+$). Incidentally, the points winter '49 and winter '50 are not uniquely defined. Therefore they have not been joined to the other points by lines indicating the sign of the phase shift.

For comparison corresponding values from Stockholm Oct. '47 to Aug. '49 are illustrated by the harmonic dial to the right in the same figure. After the deviation of the primaries by the earth's magnetic field had been corrected for, the averages of the three directions were calculated. The statistical fluctuations are great owing to the small number of days. Only days with $K_p \leqq 2^+$ were regarded as sufficiently quiet. Nevertheless the Stockholm measurements cover a far smaller area than do the Nagoya results. It even happens that the two phase shifts have opposite signs. The magnitude of the phase shift is also far bigger as regards Nagoya than Stockholm. Considering all the discrepancies between these two diagrams it seems reasonable to suggest that the seasonal variation reported by Sekido and Kodama is due to some local effect.

The Aperture of the Instruments

The measurements from Stockholm were recorded with counter telescopes having an aperture of 60° × 120°, the angle in the magnetic meridian plane being ± 30°.

Sekido and Kodama worked with three apertures: ± 12°, ± 40°, and ± 85°. Their telescopes had quadratic sections. It is remarkable that the relationship between the 12^h-component and geomagnetic activity is less apparent as regards the two large apertures (Fig. 6). A possible explanation would be the superposition of daily variations with phase shifts covering a part of the period $> \frac{\pi}{2}$. The curves of Brunberg and Dattner show that there is a concentration of initial directions in the NS-plane for varying directions of the telescopes. As regards the EW-plane curves are lacking, but a considerable spread of initial directions is indicated. Obviously the angular spread is $> \frac{\pi}{2}$.

The Components of the 12^h-Maximum

It is very difficult to resolve q_1 into components. However, during magnetically quiet days it will certainly be due to particle diffusion, the backstream of particles outside the corpuscular beams being negligible in comparison. To judge from the Stockholm measurements as well as those from Nagoya the latter component is small in itself. The big value of q_1 for magnetically heavily disturbed days will then almost entirely correspond to the flow of particles inside the beam from the sun.

By analysing the registrations from neutron monitors SIMPSON (1954) has shown that the prominent periods of maximum intensity are recurrent and indirectly associated with increased geomagnetic activity. This is also borne out by registrations in Stockholm (SANDSTRÖM 1955). Thus it appears to be well established that a corpuscular flow from the sun constitutes a part of the 12^h-component. The fluctuations registered by means of neutron monitors are bigger than those from measurements with ionization chambers and counter telescopes (SIMPSON 1954). Accordingly the soft component appears to abound in the corpuscular flow.

From counter telescope measurements SANDSTRÖM (1955) has found that there may be a small 27-day variation underlying the large recurrent increases of intensity. Apparently this variation ($\approx \pm$ 0.4 per cent) must be ascribed to the diffusion outwards of particles. As a result we cannot even in this case reckon with a component that is constant from day to day. We must also remember, that neither the regular 27-day fluctuations nor the recurrent increases of intensity reveal themselves through a daily variation. Instead they constitute a trend which tends to diminish and displace the daily maximum.

When q_1 has a positive value we are right to suppose that the inverted particle flow outside the corpuscular beams has been sufficiently big to manifest itself. However, it is equally probable that these positive values are caused by statistical fluctuations combined with the errors in the correction for the deviation by the earth's magnetic field.

Discussion

By comparing Figs. 4, 5, 6, and 7 we find that the 18^h-component can be regarded as constant except, perhaps, during prominent magnetic storms. There are actually indications that it is constant in the latter case too. As a function of time the amplitude is constant (Figs. 8 and 9). In one case only is there some contradicting evidence, namely the Nagoya measurements with a small aperture. However, when the limits of errors are taken into consideration, the points do not fall very far from the average. The difference in amplitude is not essential as regards the discussion of the constancy or non-constancy of the 18^h-component.

A certain variation of the 18^h-component correlated to magnetic storms is not at variance with theory. According to BRUNBERG and DATTNER (1954) a change of the average energy of the cosmic ray particles is to be expected when the earth is in the vicinity of a corpuscular beam. In such a case the angular correction ought to be slightly different from that derived for an average energy of 20 GeV/c. Though the amplitude will then appear to change, it really remains constant.

Another discrepancy is to be found in Fig. 6, where the displacement of the 18^h-component as registered with a large aperture on magnetically disturbed days is opposite to that found in Figs. 4 and 5.

However, the disturbance of the 18^h-component in connection with major magnetic storms is doubtful also for another reason. It has been shown (SIMPSON 1954, SANDSTRÖM 1955) that the cosmic ray changes do not exactly coincide with the increase of geomagnetic activity. Actually there is a phase shift of one or two days. As a result there should not be a very good correlation in this case, when the 18^h-component is plotted as a function of geomagnetic activity.

Summing up pros and cons it seems doubtful if the observed disturbances of the 18^h-component during increased geomagnetic activity are real.

Turning to the 12^h-component, Figs. 4, 5, 6, and 7 display consistent features. This component undoubtedly varies in a systematic way with increasing geomagnetic activity. The variations are in full accordance with the theory of Alfvén. As a function of time the 12^h-component does not vary very much, probably owing to the fact that we must of necessity calculate with averages over comparatively long periods. It appears from Fig. 9 that the amplitude of the 12^h-component was small during 1941—42. It cannot be mere chance that this period coincides with a minimum of solar activity. For quiet days it even appears to have changed into a midnight component.

Again, as regards the 12^h-components the magnitude of the variations shifts from one set of measurements to another. Part of the differences can be explained by the fact that the geomagnetic activity has been characterized in three different ways, through the K_p and C indices and the Japanese Character Figure. However, this does not explain the difference between the measurements of Sekido and Kodama with small and big apertures. When we consider the comparison made in Fig. 10 and the accompanying remarks it seems quite probable that some unknown factors cause rather large errors in the measurements with the small aperture telescope. Such an error might be due to the correction for atmospheric effects. The correction for the barometric effect has been derived from measurements with telescopes having comparatively large apertures. It is by no means certain that the same correction should be applied to instruments with a small aperture. In a direction with the zenith angle of 30° the cosmic rays have a 15 per cent longer path to traverse than in the zenith direction. The corrections for atmospheric effects should if possible be determined for each instrument individually. It ought also to be remembered that in the case of measurements with the small aperture telescope SEKIDO and KODAMA (1952) applied a correction for the temperature effect, which was omitted in the large aperture measurements. The temperature correction is no doubt less well defined than is the barometric correction.

It is evident that the results presented here are purely qualitative. Most of the measurements indicate that the amplitude of the 18^h-component is 0.13 per cent (average from the dotted lines in Figs. 4, 6, and 7) with the single value 0.38 per cent from the small aperture measurements of SEKIDO and KODAMA (1952).

More precise measurements are essential for quantitative studies of the directional components. The atmospheric effect is one of the factors limiting precision. Another such factor is the uncertainty about the average momentum of the primaries. To some extent one of these two factors can be overcome by measuring in two directions. If corrections are applied for the atmospheric effects in the conventional way, the two directions give the average momentum (BRUNBERG and DATTNER 1954) thus making it possible to find the angular correction for the time of maximum.

Conclusions

1:o There is nothing in the experimental material presented in this study which is at variance with the assumption of one 18^h-component due to a particle wind bound to the rotation of the sun and one 12^h-component consisting of a radial flow of particles (ALFVÉN 1954).

2:o The 18^h-component is invariable in correlation to geomagnetic activity of the order of $K_p \leq 5^+$.

3:o From the present material it is impossible to decide whether the 18^h-component is being disturbed or not in the case of major magnetic storms. Disturbances are not necessarily contrary to theory (BRUNBERG and DATTNER 1954).

4:o The doubtful case of major magnetic storms excepted the amplitude of the 18^h-component as a function of time appears to be constant. Observed variations are irregular and of the same order of magnitude as the limits of errors.

5:o The 12^h-component is correlated to geomagnetic activity. It is nonexistent or of reversed sign when geomagnetic activity is low. In accordance with theory the amplitude increases with increasing geomagnetic activity.

6:o The 12^h-component as a function of time displays variations outside the limits of errors. Measurements from Huancayo indicate a correlation with the sunspot cycle.

7:o A seasonal variation reported by SEKIDO and KODAMA (1952) has been compared with partly contemporary measurements in Stockholm. From this comparison and with the accuracy given by the authors it appears that the reported seasonal variation is due to some local effect.

★

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