Anisotropies in Cosmic Radiation

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Abstract

The anisotropy of the cosmic radiation outside the geomagnetic field is discussed and related to various processes in the interplanetary gas. Special attention is given to the effect of the density gradient in the cosmic ray distribution, to the earth's orbital motion and to the motion of the interplanetary gas in the solar system.

1. Introduction

Views regarding the constancy and isotropy of cosmic radiation have undergone radical changes from time to time. It is now generally agreed that there are different types of true variations of cosmic ray intensity. The importance of time variation studies arises from the light they throw on the origin and general properties of cosmic rays. A unified theory which could explain the origin and the variations at the same time would be doubly attractive.

Meteorological effects unfortunately complicate the study of the daily variation of primary cosmic ray intensity. Even after correcting for these there still remains a daily variation of a mean amplitude of about 0.2 % in the intensity measured by ionisation chamber. In the nucleonic component for which corrections for atmospheric effects are simple, there exists a true daily variation of about 0.5 to 1.0 % (CONFORTO and SIMPSON, 1957). At present all available evidence seems to indicate that the daily variation of cosmic ray intensity is related to an anisotropy of the primary radiation due to influences of the sun.

The solar daily variation of cosmic ray intensity suitably corrected for pressure, has in general only two principal harmonic components: diurnal and semi-diurnal. Some years it has been observed that the semidiurnal amplitude was of a magnitude comparable to that of the diurnal component. Hence a consideration of the changes in both is necessary to explain fully the observed daily variation. But there is a number of factors which make it appropriate to consider the two separately.

It has been shown in great detail in another paper (VENKATESAN and DATTNER, 1958) that consistent and similar changes are revealed in the amplitude and the hour of maximum of the diurnal component at the various stations in the world. It was shown that the changes in amplitude of the diurnal variation follow fairly closely the changes in geomagnetic activity as revealed by the planetary index K_p, and again the changes in the diurnal hour of maximum follow roughly the changes in solar activity as revealed by the sunspot number. There is no such consistent behaviour in the semi-diurnal component at the various stations. It appears that the semi-diurnal component is negligible at the northern high latitude station of Godhavn, and most prominent at the equatorial station of Huancayo. It seems appropriate in view of the differences between the two components, to consider them separately.

The semi-diurnal component needs careful study. It would be of importance to look into the semi-diurnal component of the nucleonic component for which there is no temperature effect involved and for which it is easier to allow for atmospheric effects. It is not possible at present to explain the cause of the semi-diurnal component.

Several effects which contribute to a diurnal variation appear as results of Alfvén's theory. These have been discussed by ALFVÉN (1954), BRUNBERG and DATTNER (1954) and SANDSTRÖM (1956). After a review of their results, we shall discuss two other possible contributions to the diurnal variation which, so far, have not been considered.

2. Alfvén's Theory

According to Alfvén, the sun has a general magnetic field which outside the sun and in the absence of corpuscular beams, approximates a dipole field during years of low solar activity. However, during periods of higher solar activity, the field should change. The corpuscular beams emitted from the sun to which the magnetic storms, aurorae, and certain types of cosmic ray effects are attributed, transport the magnetic flux outwards from the sun, as the conductivity in the space is high. The magnetic lines of force in the beam should be drawn out in such a way that the field falls off, probably in proportion to r^{-1}, as pointed out by ALFVÉN (1954). The magnetic lines of force are frozen into the interplanetary matter, which therefore takes part in the solar rotation, as pointed out by BRUNBERG and DATTNER (1954). With the gradual decrease in solar activity the lines of force should tend to go back to their original configuration of an undisturbed dipole field. There should therefore be a general movement of the field towards the sun. The outflow and backflow of the flux should obviously have the same 11-year periodicity as the solar cycle. The possibility of changes in dimensions of the region taking part in solar rotation has been pointed out by VENKATESAN (1957).

The logical consequence of this is to ask how far out from the sun the frozen-in general field of the sun extends. Obviously the solar corona should take part in the rotation. On the other hand, at great distances the centrifugal force should predominate over the magnetic forces making co-rotation impossible. It seems to be difficult to find out exactly where the limit occurs—the calculation requires more accurate data about the sun's general magnetic field and about the gas density and its distribution in the solar system. LÜST and SCHLÜTER (1954, 1955) discussed the problem, starting from an assumption of a force-free solar field and a gas density of the order of 10^3 particles/cm^3 at the orbit of Mercury. The result of this calculation was that co-rotation takes place out to Mercury's orbit. It should be pointed out that these results were obtained with a rather high assumed value of the interplanetary gas density and without taking into consideration the influence of the corpuscular beams on the shape of the magnetic lines of force.

A qualitative examination of the situation suggests the following picture: the sun, visualized as a magnetized sphere, rotates and the co-rotating matter, sticking to the lines of force, is pulled away from the sun by the action of the centrifugal force. The magnetic lines of force are thus stretched and the original dipole field of the sun is somewhat disturbed. During periods of high solar activity beams of highly conductive matter are ejected from the sun, carrying with them the magnetic field from the vicinity of the sun. The lines of force are now considerably stretched and the integrated effect of this is a distortion of the sun's general magnetic field such that it decreases much more slowly with distance from the sun than r^{-3}. A proportionality to r^{-2} has been suggested (ALFVÉN, 1956). Another effect is the increase in the region of co-rotation. As we shall see later on, there are indications from cosmic ray research which seem to be consistent with an assumption that the radius of this region is smaller than one A.U. during periods of low solar activity and bigger than one A.U. during periods of higher solar activity.

The matter in the beam moves with a velocity $\boldsymbol{v}$ and carries along a magnetic field $\boldsymbol{B}$. An observer at rest in relation to the solar system sees an electric field in the beam given by $\boldsymbol{E} = -\frac{1}{c}\boldsymbol{v}\times\boldsymbol{B}$. Such a field could be of the order of 30 μV/cm, and should then give rise to a voltage of about 10^8 to 10^9

volts across the beam. Cosmic ray particles which drift around the sun in trochoidal orbits, due to the inhomogeneity of the general solar magnetic field, would have to cross the beam, losing or gaining an amount of energy eV, where e is the charge of the particle and V is the voltage across the beam. This could produce the 27-day variation as well as the Forbush decreases, as pointed out by ALFVÉN (1950, 1956), BRUNBERG and DATTNER (1954) and VENKATESAN (1957). The beam could also produce a certain diurnal variation effect to be described later.

3. Effects contributing to the diurnal variation

Since the diurnal variation has been found to be of extra-terrestrial origin, it must be due to an anisotropy in the primary cosmic radiation. Such an anisotropy could not be caused by a cosmic ray source outside the solar system. In such a case the intensity would reveal a periodicity with sidereal time, and no such variation has so far been definitely established. Hence the solar time daily variation should have a fixed direction of anisotropy in relation to the solar system. Further, if a mechanism could be suggested according to which the direction of the anisotropy was determined by the interplanetary conditions, then the changes in the direction of the anisotropy could be accounted for by the changes in the state of the interplanetary space.

An approach which appears fruitful for the determination of the electromagnetic state in the solar system is the one based on Alfvén's model of the solar magnetic field as sketched above. As a consequence of the theory several effects immediately follow, giving rise to an anisotropy of cosmic radiation. Some of these have been discussed before and will only be briefly described here.

The effects to be described contribute anisotropies in the 0, 6, 12, and 18 hour directions respectively and are competing with each other. Thus a combination of two or more effects can result in practically any direction of anisotropy. This does not make the solution arbitrary, since the relative importance of the effects can be determined from the conditions in interplanetary space which are known from other observational facts like studies of solar activity, geomagnetic disturbances, auroral activity, ionospheric and other effects. Below we discuss the various sources of anisotropy.

I. Anisotropy due to the particles being carried by the magnetic field of the beams.

The corpuscular beams ejected from the sun carry a frozen-in magnetic field and the field moves with a velocity which can be estimated from the time between a solar flare and the incidence of magnetic disturbances at the earth. The cosmic ray particles which move out with the lines of force receive an additional velocity component superimposed on their isotropic motion. This will cause an anisotropy and a diurnal variation with a maximum at 12 h. According to COMPTON and GETTING (1935) the amplitude of the diurnal variation will be given by

$$n'/n = 1/(1-\beta \cos \omega')^3$$

where n'/n is the normalized number of particles impinging on a surface moving with a velocity βc, c being the velocity of light, and ω' is the angle between the velocity vector of the moving surface and the direction of the moving particle assuming its velocity to be almost equal to that of light. For monochromatic primaries and a velocity of 10^8 cm per sec within the beam we get

$$n'/n \approx (1+\beta \cos \omega')^3 = 1 + 0.9 \cdot 10^{-2}$$

for $\omega' = 0$, and $\beta c = 10^8$ cm/sec $= 0.003\ c$. Thus the amplitude of the diurnal variation caused by this anisotropy could be of this order when the beam hits the earth and only monochromatic primaries are taken into account. For primaries having an energy distribution function a suitable modification is necessary, as has been pointed out by BRUNBERG and DATTNER (1954).

II. Anisotropy due to the backflow of the magnetic flux to the sun.

In connection with the 12 hour anisotropy we mentioned the outward motion of particles with the storm producing corpuscular beams. During the same periods the outflow of magnetic flux is taking place. Alfvén has pointed out that such a process would empty the solar magnetic flux in a rather short time. This difficulty is overcome if we make the logical assumption that the lines of force which have been pulled out cantract gradually to their original position like elastic strings. Such a process would result in the gradual recovery of the dipole character of the general solar magnetic field, and conserve in the long run the magnetic flux of the sun. Thus after the storms there would be a motion of the magnetic field lines and hence of the cosmic ray particles across the earth's orbit towards the sun. It is difficult to determine the amplitude of the diurnal variation that arises but it is likely that it is of the order of less than 0.04 % and the time of maximum 24 h. The effect II must cancel the effect I in an annual overage, since the life-time of a beam is short compared to one year and all the particles carried away by a beam have to diffuse back in a time that is short compared to the life-time of a beam. Otherwise the region inside the earth's orbit would be completely emptied during periods of high solar activity.

III. Anisotropy due to the generation of cosmic ray particles.

ALFVÉN (1954) has suggested that cosmic ray particles are first accelerated in the vicinity of the sun and that there is then a general outflow of cosmic ray energy away from the sun and across the earth's orbit. This, again, causes an anisotropy and a diurnal variation with an amplitude of 0.04 % and a maximum at 12 o'clock. Such an effect would naturally be more noticeable in the years of decreasing solar activity. In the years of increasing solar activity there could be a reversed direction of anisotropy.

IV. Anisotropy due to the rotation of the solar magnetic field.

During the more active years of the solar cycle the neighbourhood of the sun, probably as far as beyond the earth's orbit, is filled with a highly conducting medium which takes part in the solar rotation along with the sun's general magnetic field. The angular velocity of this rotation is $\omega = 2\pi/27 \cdot 24 \cdot 3{,}600$ and gives a linear velocity directed parallel to the earth's orbit, i.e. the 18 hour direction, $v = \omega' \cdot R_{S\text{-}E}$, where $R_{S\text{-}E}$ is the earth's orbital radius. This velocity should be superimposed on the isotropic motion of the cosmic ray particles and would cause a diurnal variation of amplitude 0.39 % for monochromatic primaries as discussed by BRUNBERG and DATTNER (1954). As was pointed out there and by S. LUNDQUIST (1954) some slight modification is necessary for primaries with an energy distribution function.

V. Anisotropy during the recovery after a magnetic storm.

During the days immediately following magnetic storms certain particles should have to cross the beam as pointed out by BRUNBERG and DATTNER (1954), K. NAGASHIMA (1955), L. J. DORMAN and E. L. FEINBERG (1956) and DATTNER and VENKATESAN (manuscript under preparation). By a graphical method the latter have drawn the orbits of cosmic ray particles, in the equatorial plane of the sun, hitting the earth in directions corresponding to local times 0, 3, 6, . . ., hours. From the result it was seen that such orbits as enter in directions corresponding to local times 3, 6 and 9 hours (neglecting the deflection in the geomagnetic field for which one could apply a correction later) are periodic and hence must cross the beam and be retarded. This would give rise to a minimum around 6 hours which is the same as a maximum at 18 hours. It is obvious that the amplitude of the corresponding diurnal variation should be less than the amplitude of the decrease connected with the storm. This effect would, in an annual average, be of importance during years of high geomagnetic activity.

VI. Anisotropy due to the earth's orbital motion.

It has been suggested that the dimensions of the part of the solar system taking part in the solar rotation vary with time during the solar cycle. It is likely that this region is biggest at the time of maximum and smallest at the time of minimum solar activity. Thus, during a period of very low solar activity as in, say, 1954, the earth may be situated outside this region. Hence the medium around the earth is at rest in relation to the earth's orbit. While the earth moves in its orbit, it receives more particles on its morning side than on its evening side. The amplitude of the diurnal variation thus arising, as given by the Compton-Getting formula, would be about 0.03 %. However, this variation, which should be observed at the time of solar minimum, need not necessarily take place in every solar cycle, unless the solar activity is so low that the earth is likely to be outside the region taking part in the solar rotation.

VII. Anisotropy due to a gradient in the density of cosmic ray particles.

This effect can be understood from a two-dimensional study of the motion of charged particles in a magnetic field.[1]

Let us consider a cloud of charged particles moving in random directions in a plane in an inhomogeneous magnetic field. If the particle density within the cloud was independent of space co-ordinates and if we were to determine the number of particles arriving per unit time at the surface S within an angle α, this would not vary with the angle between the direction of measurement and the lines of constant magnetic field strength (see fig. 1). Fig. 1 and 4 show the situation in the plane perpendicular to the magnetic field. Thus the surface S is represented by a straight line and α is a plane angle. The measuring device will not measure any anisotropy (SPITZER, 1956). This can be understood physically from fig. 2. In spite of the fact that the particles drift to the left we find that, for any arbitrary point P, and for a certain energy, equal numbers of particles arrive from both sides, as the density is constant.

But if we now introduce a density gradient parallel to the field gradient as in fig. 3, where the thickness of the line represents the

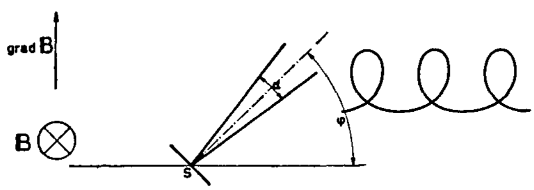

Fig. 1. A two-dimensional picture of a cosmic ray recording apparatus with an area S and aperture α together with a cosmic ray particle orbit in an inhomogeneous magnetic field.

number of particles in the orbit, we find that more particles arrive from the right than from the left. Thus we observe an anisotropy in the particle density. Now we wish to express the intensity measured by the device in fig. 4, as a function of the angle φ.

A field gradient alone (i. e., without any density gradient) does not introduce any anisotropy. On the other hand it is easy to see from SPITZER (1952) that a density gradient

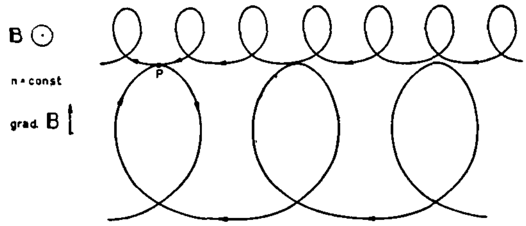

Fig. 2. Cosmic ray orbits passing through point P.

should cause an anisotropy even in a homogeneous field. We do not know the contribution from the inhomogeneity of the field. Probably it contributes only second order effects. For the present we neglect the inhomogeneity of the field and calculate the anisotropy for the two-dimensional case.

For a device such as in fig. 4 the particle spectrum $f(\varrho)$ is the number of particles within a velocity interval corresponding to Larmor radii ϱ to $\varrho + d\varrho$ arriving per unit length, unit angle, and unit time. The particles move in circles and each particle has a fixed centre of gyration. Further, there are n centres of gyration of particles with Larmor radii in the interval ϱ to $\varrho + d\varrho$ per unit area (not unit volume as we are considering the two-dimensional case). The distribution function $n(x, \varrho)$ is a function of ϱ, and at the same time a function of x, which expresses the fact that there is a finite density gradient along the x-axis. We make the following assumption about this function

$$n(x, \varrho) = e^{-\text{constant} \cdot x} \cdot g(\varrho)$$

i.e., an exponentially decreasing density with decreasing field. The density gradient would then be proportional to n.

$$\frac{\delta n}{\delta x} = - n \cdot \text{constant}$$

Thus the density would change with a certain fraction per unit distance and this fraction/unit distance would be constant along the x-axis. It is important to remember that $n(x, \varrho)$ is

[1] For a complete study of the problem see E. ÅSTRÖM. (1959).

the density of the centres of gyration and not the particle density; the interchange of these quantities can lead to considerable errors and general confusion.

Let us calculate the number of particles measured per unit time by the device within

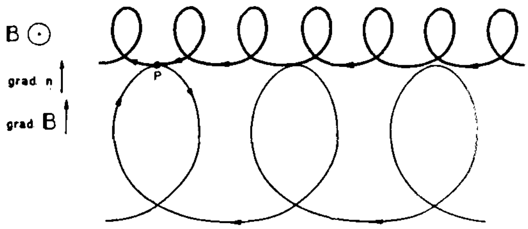

Fig. 3. Cosmic ray orbits passing through point *P*. Line thickness indicates the number of particles in the orbit.

the interval ϱ to $\varrho + d\varrho$, at an angle φ. From fig. 4 we find that the particles entering the measuring device have their centres of gyration in the shaded area. The area is equal to $S\varrho\alpha$, where S is a length corresponding to the area of the apparatus. The particles perform $u/2\pi\varrho$ revolutions per second if u is the particle velocity and there are $n(x, \varrho)$ centres of gyration per unit area. Thus,

$$f(\varrho)_\varphi \cdot S \cdot \alpha \cdot d = n\ (x, \varrho) \cdot S \cdot \varrho \cdot \alpha \cdot \frac{u}{2\pi\varrho}\ d$$

and

$$f(\varrho)_\varphi = \frac{u}{2\pi} n\,(x, \varrho)$$

The dashed area is situated at $x = -\varrho \cos \varphi$ and a series expansion gives

$$f(\varrho)_\varphi = \frac{u}{2\pi}\left[n\,(0, \varrho) - \frac{\delta n}{\delta x}\,\varrho\cos\varphi + \right.$$
$$\left. + \frac{1}{2}\frac{\delta^2 n}{\delta x^2}\,(\varrho\cos\varphi)^2 \ldots\right]$$

and neglecting derivatives of higher order than one we obtain

$$f(\varrho)\,\varphi = \frac{u}{2\pi} n\ (0,\ \varrho)\left(1 - \frac{1}{n\ (0,\ \varrho)}\frac{\delta n}{\delta x}\,\varrho\ \cos\ \varphi\right)$$

For $x = 0$, and $\varphi = \frac{\pi}{2}$ we get

$$f(\varrho)_{\frac{\pi}{2}} = \frac{u}{2\pi} n\ (0,\ \varrho)$$

which is the spectrum of the particles. Hence

$$f(\varrho)_\varphi = f(\varrho)_{\frac{\pi}{2}} + \varkappa f(\varrho)_{\frac{\pi}{2}}\ \varrho\ \cos\ \varphi$$

where

$$\varkappa = \frac{1}{n\ (0,\ \varrho)}\frac{\delta n}{\delta x}$$

Integrating over all energies we get the intensity in direction φ

$$I_\varphi = \int_0^\infty f(\varrho)_\varphi\, d\varrho = \int_0^\infty f(\varrho)_{\frac{\pi}{2}}\, d\varrho + \varkappa \int_0^\infty f(\varrho)_{\frac{\pi}{2}}\,\varrho \cos \varphi d\varrho$$

and the amplitude of the intensity variation with angle φ would be

$$\frac{I_0 - I_{\frac{\pi}{2}}}{I_{\frac{\pi}{2}}} = \varkappa \cdot \frac{\varkappa \int_0^\infty f\,(\varrho)_{\frac{\pi}{2}}\ \varrho d\varrho}{\int_0^\infty f\,(\varrho)_{\frac{\pi}{2}}\, d\varrho}$$

The above discussion can be directly applied to the study of cosmic rays. If the density of

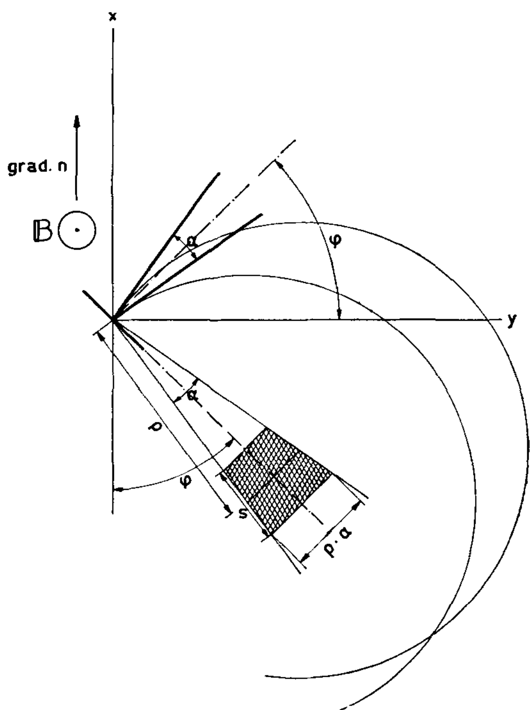

Fig. 4. A two-dimensional picture of a cosmic ray recording apparatus with an area *S* and aperture *α*. The particle orbits are circular since *B* is assumed constant. The centres of gyration for particles recorded by the apparatus are situated within the shaded area.

cosmic ray particles decreases outwards from the sun we should measure a different intensity on the morning and evening sides. In fact if the solar magnetic dipole is parallel to the geomagnetic dipole, we should expect a diurnal variation with a maximum at 6 hours and an amplitude outside the atmosphere equal to

$$\frac{\Delta I}{I} = \frac{\varkappa \int_0^\infty f(\varrho)\, \varrho d\varrho}{\int_0^\infty f(\varrho)\, d\varrho}$$

where $\varkappa$ has been defined earlier, and $f(\varrho)$ is the primary spectrum of cosmic rays. It should be pointed out that the spectrum has been transformed from energy spectrum, to Larmor radii spectrum, using the formula for Larmor radius for relativistic particles

$$\varrho = \frac{1}{eBc} \sqrt{e^2 V^2 + 2\, eVm_0\, c^2}$$

However, in order to obtain the amplitude at sea level we must use, not the primary spectrum, but the effective spectrum, i.e. the primary spectrum times the multiplicity of cosmic rays due to the interactions in the atmosphere.

From directional measurements it has been suggested that the main contribution to the daily variation could be considered to be due to particles with energies near 25 *GeV*. If we assume the radiation to be monochromatic, we obtain the following expression for the amplitude

$$\frac{\Delta I}{I} = \varkappa \varrho$$

and for particles with energy 25 *GeV*, $\varrho = 0.87 \cdot 10^{11}$ m in a field of 10 micro gauss. Thus we find the value of $\varkappa$ that corresponds to the measured magnitude of the variation, $\frac{\Delta I}{I} = 0.1\,\%$, to be $\varkappa = 1.2 \cdot 10^{-14}\,\mathrm{m}^{-1}$. This means that the density of cosmic ray particles may not vary more than roughly 1 % over half an astronomical unit. This has to be specially emphasised since such a constancy of cosmic ray distribution in space is absolutely necessary in order not to cause a diurnal variation bigger than that observed.

A theoretical determination of the amplitude of the 6 hour component of diurnal variation due to the density gradient is difficult, since not much is known about the distribution of cosmic ray particles in the interplanetary space. Further, it is difficult to decide how a possible density gradient would vary with solar activity. The purpose of the discussion has been to point out a probable effect, to explain how the variation of the 18 hour component is possible and to show that an earlier hour diurnal maximum is not incompatible with the theory. Further, the changes in the density gradient could, to a certain extent, account for the day to day changes in the diurnal variation.

4. Discussion of observed diurnal variation

For a comparison of the results anticipated from the theory with measurements, we use the daily variation data of the Carnegie Institution Ionisation Chamber for the period 1937—1955. The mean diurnal variation for each year is determined for the stations Huancayo, Cheltenham and Christchurch. It is then corrected for geomagnetic deflection using the Brunberg-Dattner curves assuming an energy of 25 GeV for the primaries. The propriety of using this value has been discussed at length by them (Brunberg and Dattner, 1954) The correction for Cheltenham and Christchurch is most reliable and is about 45°, or three hours, for both stations. For Huancayo the correction is rather uncertain, but correction of 90°, or six hours, seems to give a fair agreement. It could however be higher.

The corrected diurnal component for each year is then resolved along the 0 and 6 hour directions. A positive value for the 0 hour component then indicates that it predominates over the 12 hour component. We can only observe the net result of both. Similarly a positive value for the 6 hour component indicates that this is more prominent than the 18 hour component. As pointed out earlier the observed diurnal component is the net result of the four directional anisotropies, which compete with each other to a greater or lesser extent.

Fig. 5 gives the 0 hour and 6 hour components for all the three stations as well as the mean of three. Fig. 6 shows the mean together with a measure of solar activity as revealed by the mean annual sunspot number R and a

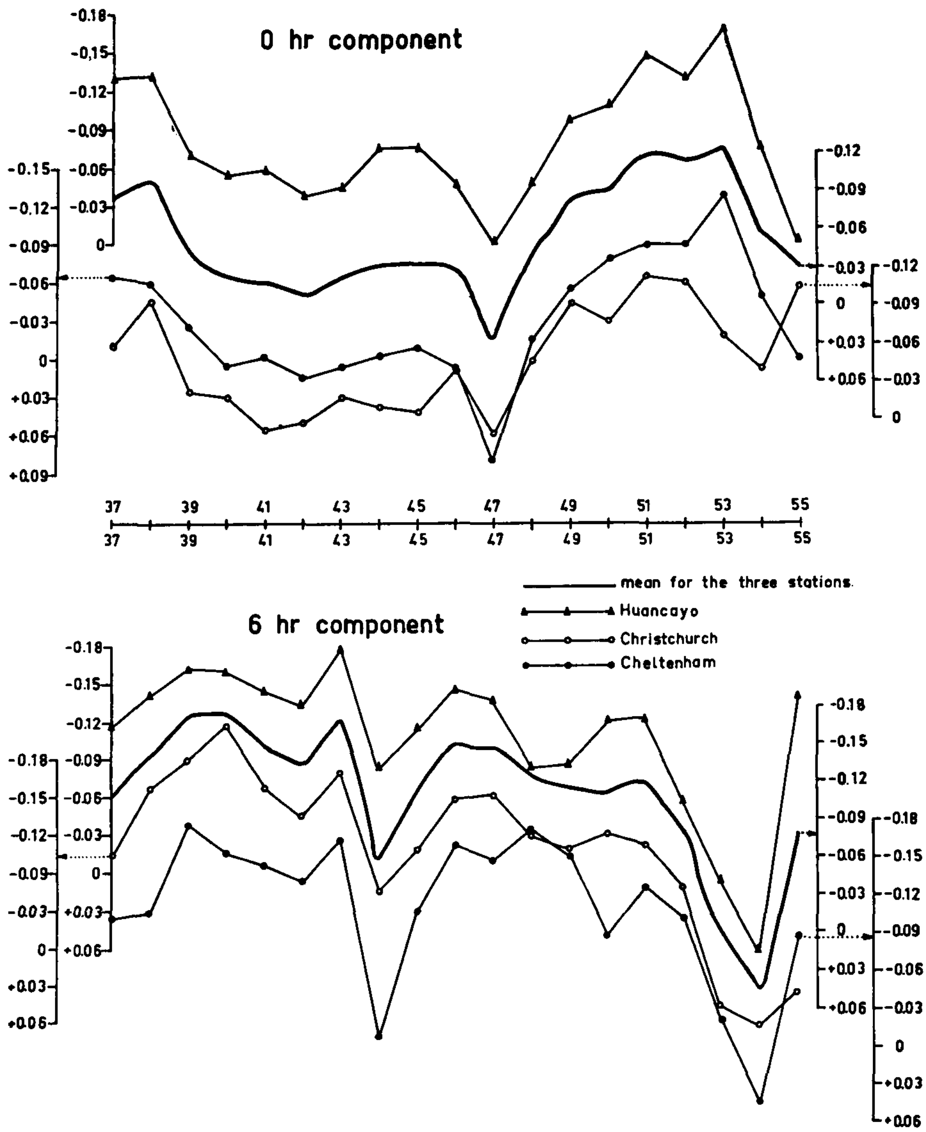

Fig. 5. The amplitude of o hr component (at the top) and 6 hr component (at the bottom) of the diurnal variation in the primary cosmic ray intensity outside the geomagnetic field. (Huancayo, Cheltenham and Christchurch 1937 – 55.)

measure of geomagnetic disturbance as revealed by the cumulative K_p for the 60 most disturbed days in each year.

There are certain essential differences between the K_p curve and the R curve. Normally, one would have expected the measure of geomagnetic disturbance to follow the solar activity fairly closely, as the former is attributed to the latter. It should be noted, however, that the geomagnetic disturbance continues to be prominent to the same extent during the period 1938—1941 although solar activity is rapidly decreasing. Again in 1943, almost towards the end of the solar cycle there is a sudden increase in geomagnetic activity. Further, in 1948, when the solar activity is maximum, we have a minimum of geomagnetic disturbance, which then rises again as

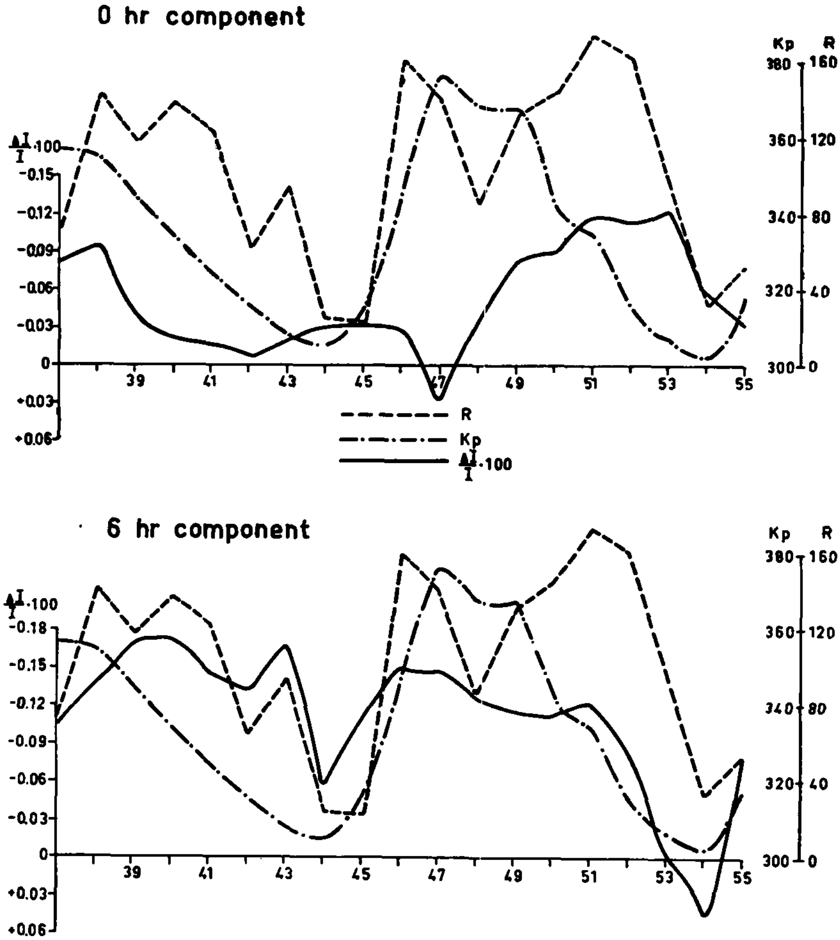

Fig. 6. The mean of the curves in fig. 5 plotted together with the sunspot number R and the sum of K_p values for the 60 most disturbed days of each year.

solar activity rapidly decreases. This suggests that the characteristics of the beams, like the frozen-in field and the resulting electric field, change. Hence the combined effect of phenomena, some of which depend on solar activity and some on the properties of the beam, is likely to give a confused picture.

It can be seen that the 6 hour component follows the geomagnetic disturbances fairly closely. There is a slight departure only in the case of Cheltenham for the years 1948 and 1949, which needs looking into. In this connection it is proper to point out that one should not always expect the beams emitted to be symmetrical with respect to the earth and this could very well complicate the issue.

The region taking part in solar rotation should naturally depend indirectly on solar activity and directly on the activity of the beams. The 18 hour component, appearing after a magnetic storm, should also depend on the geomagnetic activity, which reflects the activity of the beams. Only when the solar activity is so small that the earth gets out of the region taking part in solar rotation, should there be a 6 hour component arising from the earth's orbital motion. This appears to have taken place in 1954 when we observed the positive value which reflects the predominance of the 6 hour component. Here the normal 18 hour component is absent since the earth is outside the region taking part in solar rotation. Superimposed on these we might have the 6 hour component due to the density gradient, the dependence of which on solar activity is unknown. In general the 18 hour component seems to fit in with the theory.

The 0 hour component is a mixture of opposing kinds of effects which confuse the general picture somewhat. The anisotropy due to generation of cosmic ray particles should give an increase in the diurnal component when solar activity reaches a minimum and vice-versa, as pointed out by ALFVÉN, (1954). The 12 hour component arising from the particles being carried by the field of the beam followed by the backflow or the 24 (0) hour component should show a maximum when solar activity is maximum, or rather it should also depend on the characteristics of the beam. However the latter effects cancel in an annual average and hence do not appear in the diagrams. The net result observed is that the 12 hour component shows a maximum in 1944, a minimum in 1947, and a maximum around 1952—1954 and shows a tendency to exhibit a minimum again in the approaching solar maximum of 1957. In 1937—1938, however, it does not show a minimum. In fact the value does not go down until 1939. It is not clear whether the shift in the maxima between the R and K_p curve has anything to do with this. Again there is a prominent 0 hour component in 1947 when the R and K_p curves show opposite trends. All this needs careful consideration and a study of the characteristics of beams, their changes and origin, and their variations with solar activity might throw more light on apparent discrepancies.

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REFERENCES.

ALFVÉN, H., 1954: On the origin of cosmic radiation. *Tellus:* **6**, pp. 232—253

ALFVÉN, H., 1956: The sun's general magnetic field. *Tellus;* **8**, pp. 1—12

ALFVÉN, H., 1950: On the solar origin of cosmic radiation II. *Phys. Rev.:* **77**, pp. 375—379

BRUNBERG, E.-A. and DATTNER, A., 1954: On the interpretation of the diurnal variation of cosmic rays. *Tellus:* **6**, pp. 73—83

BRUNBERG, E.-A. and DATTNER, A., 1954: Variation of cosmic ray intensity during a magnetic storm, *Tellus:* **6**, pp. 254—259

COMPTON, A. H. and GETTING, I. A., 1935: An apparent effect of galactic rotation on the intensity of cosmic rays. *Phys. Rev.:* **47**, pp. 817—821

CONFORTO, A. M. and SIMPSON, J. A., 1957: The 24-hour intensity variation of the primary cosmic rays. *Il Nuovo Cimento:* **5**, pp. 1052—1062

DORMAN, L. I. and FEINBERG, E. L.: *Proceedings of the V. International Congress of Cosmic Radiation, Guanajuato, 5—13 Sept. 1955:* On the nature of the cosmic ray variations, pp. 393—432

LUNDQUIST, S., 1954: A note on the variation of cosmic ray intensity produced by an electric field. *Tellus:* **6**, p. 260

LÜST, R. and SCHLÜTER, A., 1954: Force free magnetic fields. *Z. f. Astrophys:* **34**, pp. 263—282

IBID. 1955: Angular momentum transport by magnetic fields and the breaking of rotating stars. *Z. f. Astrophys:* **38**, p. 110

NAGASHIMA, K., 1955: The diurnal variation of cosmic rays. *J. Geomag. Geoel:* **7**, pp. 51—68

SANDSTRÖM, A. E., 1956: The 24-hour averages of cosmic ray intensity in Stockholm 1947—48 and 1954. *Tellus:* **8**, pp. 13—17

SPITZER, L. Jr., 1952: Equations of motion for an ideal plasma. *Astrophysical J.:* **116**, pp. 299—316

SPITZER, L. Jr., 1956: *Physics of fully ionized gases.* Interscience Publishers Inc., New York

VENKATESAN, D. and Dattner, A., 1959: Long term changes in the daily variation of cosmic ray intensity. *Tellus:* **11**, pp. 116—129.

VENKATESAN, D., 1957: Changes in amplitude of the 27-day variation in cosmic ray intensity during the solar cycle of activity. *Tellus:* **9**, pp. 117—125

ÅSTRÖM, E., 1959. On the density and isotropy of an ionized gas in a magnetic field. *Tellus:* **11**, pp. 250—253.