AN INTERPRETATION OF THE SOLAR ANISOTROPY OF PRIMARY COSMIC RADIATION

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I. INTRODUCTION

The study of the daily variation of cosmic ray intensity has grown in importance in recent years with increasing realisation that it provides a powerful tool for understanding the anisotropy of primary cosmic radiation as well as the electromagnetic state in interplanetary space. With the solar daily variation of cosmic ray intensity which arises due to the spin of the earth, it is possible to investigate the anisotropy in various directions by making suitable directional studies at different latitudes. A mass of data collected during the last three or four years as well as a re-examination of earlier data have brought to light numerous experimental facts which have been reviewed recently by Sarabhai et al. The relevant facts may be stated as follows:

1. The daily variation cannot at all times be satisfactorily described in terms of the diurnal component alone. It has been observed, however, that in general the first two harmonic components are adequate to represent fairly satisfactorily the main features of the daily variation.

2. The 12-monthly (annual) mean daily variation of meson intensity exhibits large long-term changes of amplitude and of the time of maximum of the diurnal as well as the semi-diurnal components.

3. During several years the 12-monthly mean daily variation, particularly at low latitudes, exhibits two maxima instead of one (Fig. 8 of Ref. 2). Sarabhai et al. have tried to show that the 12-monthly mean daily variation can be explained in terms of two types of variations, one having a maximum during the day at about 1100 to 1300 hours and the other at night at about 0100 to 0300 hours. The relative contribution of these two types of variations changes from year to year and the data collected over the past twenty years is suggestive of a relationship of these changes with the 22-year cycle of solar activity. This makes the maximum of the diurnal component of the daily variation shift by as much as 10 to 12 hours over a number of years.
4. When data on individual days are examined, there is a tendency for the time of maximum of the diurnal component to occur either at noon or during the early morning hours. Such days usually occur in groups that sometimes recur after 27 days. Some of the groups appear to be associated with active solar regions.

5. High values of $C_p$, daily geomagnetic planetary index, are normally associated with days having large amplitudes. However large amplitudes are not always associated with magnetically disturbed days or the central meridian passage of solar regions of visible activity.

The above facts lead to the conclusion that the daily variation and the anisotropy of cosmic radiation either on individual days or averaged over a group of days is of a highly variable character. Our knowledge of the permanent anisotropy, if indeed it exists, is meagre at the present moment. Hence for the interpretation of the anisotropy it is appropriate for the time being to take into account only the variable anisotropy about which we have a number of well established facts regarding its form as well as its solar and terrestrial relationships.

In the past few years, several attempts have been made to explain some of the average characteristics of the diurnal component of the daily variation on a model involving the modulation of primary cosmic ray intensity by changes in the electromagnetic condition in interplanetary space. Brunberg and Dattner have tried to explain an anisotropy which would produce a daily variation of average amplitude of 0.3% and a time of maximum near noon. They suggest that a tangential anisotropy in the 18-hour direction might be created in the solar system by the rotation of the magnetic field of the sun. Alfven has moreover shown that the disturbance in this field by the solar emission of ionised matter can give rise to a radial anisotropy which would alter with solar activity and could therefore account for the 11 years variation in the time of maximum of the diurnal component shown by Sarabhai and Kane and Thambyahpillai and Elliot.

To explain the anisotropy on days when there is a magnetic storm, Nagashima has studied in detail the implications of the suggestion made by Elliot and Dolbear and Alfven that the storm time anisotropy is due to the presence of a polarised beam of ionised matter in the vicinity of the earth. His analysis shows that this anisotropy in the primary radiation is directed along the 12-hour direction and explains for the first time the increase in amplitude and advancement of the phase of the diurnal variation on magnetically disturbed days.
Apart from the difficulty that arises due to the daily variation exhibiting characteristics markedly different from those assumed by Brunberg and Dattner, none of the theories advanced so far accommodate the existence of the two main types of variable anisotropies which are responsible for the day and night maxima in the daily variation of cosmic ray intensity at low latitudes. In this paper an attempt has been made to understand the variable character of anisotropy by modulation of the primary cosmic ray intensity by ionized solar-matter as it is ejected from the sun carrying a frozen magnetic field. The anisotropy is derived from the measurements of the daily variation of meson intensity at low latitudes.

II. CHARACTERISTICS OF THE SOLAR CORPUSCULAR EMISSION

The recurring disturbances in the earth's magnetic field have been attributed by a number of workers to the presence of streams of ionized matter emitted by the sun. Although a 27 days recurrence of these disturbances over two to three solar rotations suggests that the emission is active over a long period, individual disturbances last for a few days. This indicates that the earth is engulfed in the streams for only a few days. It is, therefore, assumed that a mass of gas ejected by the sun may be looked upon as a beam with parallel sides perpendicular to the plane of the ecliptic.

Alfvén has shown that a highly conducting medium moving out of a region having a high magnetic field tries to drag the field with it. A mass of gas which is expelled by the sun is ionized and he has suggested that it will carry with it the solar magnetic field. Recent work on the general magnetic field of the sun by Babcock and Babcock puts a limit of 1 gauss to its magnitude and suggests that it is concentrated near the polar regions. In solar equatorial latitudes there are intense local magnetic fields associated with active regions on the sun. It is reasonable to expect that beams along the plane of the ecliptic are formed by solar corpuscular emission from solar equatorial latitudes and they would carry therefore a trapped field which is not derived from the general solar dipole field but from the local magnetic fields in the neighbourhood of active regions from which the ionized matter is supposed to be emitted. On this basis it would be possible to have the trapped field having no preferential orientation with respect to the solar dipole field. For simplifying calculations it is assumed that this field is uniform within the beam. Swann has explained how such uniformly magnetized beams with no external magnetic field can be realised in practice.

The trapped magnetic field moves with the beam with the same velocity as the solar corpuscles and in a co-ordinate system moving with the co-
puscles, there is only a magnetic field present. But an observer on the earth, with respect to which the magnetic field is in motion, observes in addition to a magnetic field a charge displacement in a direction perpendicular to the velocity of the beam and the magnetic field. The beam therefore appears to have crossed electromagnetic fields and cosmic ray particles traversing the beam gain or lose energy depending upon their orientation with respect to the electric field. An isotropic distribution of primary particles is disturbed and an anisotropy is created in some directions in space.

III. ANISOTROPY OF THE PRIMARY COSMIC RADIATION*

In evaluating the effect of a beam of solar ionized matter on the anisotropy of primary cosmic radiation we neglect the inclination of the axes of the sun and the earth with the ecliptic. For observing stations at low latitudes, the primary cosmic ray particles incident from the vertical come from directions close to the equatorial plane, and hence only the acceleration or deceleration of particles crossing the beam in this plane is of consequence. This is produced by an electric field which develops due to the component of the trapped magnetic field in a direction perpendicular to the plane of the ecliptic. With different orientations of the magnetic field within the beam, this component could be reversed in direction. In the present work, the effect of this component alone on the anisotropy of cosmic radiation is investigated, and the results are most closely applicable to observations at the equator with narrow angle telescopes pointing to the vertical. However omnidirectional instruments, such as the ionization chamber, measures in addition primary particles inclined to the equatorial plane. In this case, as well as for observations at high latitudes, the contribution of the component of magnetic field parallel to the ecliptic would also have to be considered.

Fig. 1 shows the cross-section of the beam in the plane of the ecliptic. The ionized matter in the beam is moving with a velocity \( v \) along the Y-axis. The beam has a width equal to \( b \) along the X-axis. It is supposed that the beam is situated symmetrically with respect to the plane of the ecliptic. The magnetic field trapped within it has a component \( H_z' \) along the Z-axis and is called positive along the positive direction of the Z-axis. To a stationary observer on the earth the beam will have a component of magnetic field \( H_z = H_z'/(1 - v^2/c^2)^{1/2} \) along the Z-axis and an electric field \((v/c) H_z\) along the X-axis. The potential difference between the two parallel sides of the beam is therefore \((v/c) b H_z\) and cosmic ray particles of charge \( e \) crossing such a beam will change their energy by \((v/c) e b H_z\).

* Part of the analysis in this section is reproduced from the original paper by Nagashima.
The direction of the velocity of a particle in space can be uniquely determined by two angles $\phi$ and $\psi$ where $\phi$ is the inclination to the plane of the ecliptic (XOY plane in Fig. 1) and $\psi$ is the inclination in the plane of the ecliptic to the sun earth line (Y-axis in Fig. 1). If $W_1$, $(\phi_1, \psi_1)$ represent the energy and the direction of the particle before entering the beam and $W_2$, $(\phi_2, \psi_2)$, those of the particle after crossing the beam we get

$$\Delta W_b = W_2 - W_1 = (v/c) ebH_z$$

(1)

Since the velocity of ionized matter in the beam is much less than the velocity of light, $v \ll c$. Also if $\Delta W_b < W_1$ the direction of the particle with respect to the plane of the ecliptic is not appreciably altered. In consequence

$$\phi_2 \approx \phi_1$$

The particle is however deflected in the plane of the ecliptic and as shown in Fig. 1 if $\phi$ is not very large

$$\cos \psi_2 = \cos \psi_1 - b/\rho_\phi$$

$$= \cos \psi_1 - \sec \phi (ebH_z/W_1)$$

(2)

where $\rho_\phi$ is the projection of the radius of curvature on the plane of the ecliptic.

It is seen from Eq. 2 that if $b > 2\rho_\phi$, $\cos \psi_2 < -1$ and $\psi_2$ is imaginary. Such particles are not able to cross the beam but after entering the beam are deflected so as to emerge with unchanged energy on the same side of it from which they entered. Particles having $b < 2\rho_\phi$ can cross the beam only if
they enter it in favourable directions. The energy \( W \) of a proton which can cross the beam of width \( b \) in a direction \( \phi \) is given by

\[
W = W_{\min}(\phi, b) = \frac{1}{2} ebH_z \sec \phi
\]  

In Fig. 2 have been shown the deflections in the plane of the ecliptic of particles having energy less than \( W_{\min}(0, b) \). It is noticed that if initially there is an isotropic distribution of such particles, the deflections within the beam do not alter the intensity of these particles in any direction outside the beam. Thus the isotropy of cosmic radiation of energy less than \( W_{\min}(0, b) \) is not disturbed by the beam when an observer is outside it. If, on the other hand, the earth is within the beam, the particles have to cross only a part of the beam to reach the earth. Since the strength of the magnetic field is the same as before but the width is reduced, the minimum energy of particles which can reach the earth is reduced and the anisotropy therefore extends to particles with energy less than \( W_{\min}(0, b) \). When the earth is at a distance \( x \) from one side of the beam, the minimum energy of the anisotropic radiation \( W_{\min}(0, x) \) is given by

\[
W_{\min}(0, x) = \frac{1}{2} exH_z \text{ or } \frac{1}{2} e (b - x) H_z
\]  

whichever is smaller.

The anisotropy of cosmic rays also depends on the position of the earth with respect to the beam. The distance between the earth and the beam
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changes due to the spinning of the sun and the motion of the earth along the ecliptic. Beams approach the earth in the same direction as the motion of the earth, but soon overtake it. We have to consider three cases; firstly when the beam approaches the earth, secondly when it envelops the earth and finally when it recedes from the earth. In Fig. 3 we show the effects in each case when \( H_z \) is positive. When the observer is on the right side of the beam, particles of energy \( W \) after crossing the beam from left to right gain an energy \( \Delta W_b \) and have their final velocity directions lying in the shaded region in Fig. 3(a). This region of acceleration extends from \( \psi_b^{acc} \) to \( \pi \) where \( \psi_b^{acc} \) is given by Eq. 2 as

\[
\psi_b^{acc} = \cos^{-1}\left(1 - 2 \sec \phi \frac{W_{\min}(0,b)}{W}\right)
\]  

(5)

There will be an increase of intensity of particles arriving in directions lying in this region, while those arriving from other directions either have not passed through the beam or, if passed through, have not crossed the beam and therefore do not undergo any change in their energy or intensity.

In Fig. 3(b), the earth is enveloped in the beam but is at a distance \( x \) from the left side of the beam. The beam can now be considered as made up of two parts, one having width equal to \( x \) and the other \( (b-x) \). Particles arriving from the left side are accelerated and gain an energy by \( \Delta W_x = (\nu/c) exH_z \) and those coming from the right are decelerated and lose energy by \( \Delta W_{(b-x)} = (\nu/c) e(b-x)H_z \). Due to the deflection of particles within the beam, the region of acceleration extends from \( \psi_x \) to \( \psi_{(b-x)} \) while that of deceleration from \( \psi_{(b-x)} \) to \( \psi_x \) where

\[
\psi_x = \cos^{-1}\left(1 - 2 \sec \phi \frac{x}{b} \frac{W_{\min}(0,b)}{W}\right) \text{ and } \pi > \psi_x > 0
\]

(6)

\[
\psi_{(b-x)} = \cos^{-1}\left(-1 + 2 \sec \phi \frac{b-x}{b} \frac{W_{\min}(0,b)}{W}\right) \text{ and } 2\pi > \psi_{(b-x)} > \pi
\]

(7)

When the earth is in the centre of the beam, \( i.e., x = b/2, \psi_x \) and \( \psi_{(b-x)} \) are separated by 180°. We thus see that when the earth is within the beam, all directions in space, as viewed from the earth, are divided into either accelerated or decelerated regions. The intensity of the particles will therefore be more or less according as the instrument points to the region of acceleration or deceleration respectively.

In Fig. 3(c) the earth is on the left side of the beam and particles of energy \( W \) while crossing the beam lose their energy by \( \Delta W_b \) and appear in a shaded region bounded by \( \psi_b^{dec} \) and \( 2\pi \) where
In this region the intensity of the particles is below normal.

\[ \psi_{\phi}^{\text{dec}} = \cos^{-1} \left( -1 + 2 \sec \phi \frac{W_{\min}(0, b)}{W} \right) \text{ and } 2\pi > \psi_{\phi}^{\text{dec}} > \pi \]  

FIG. 3. Deflections of primary particles of energy \( \approx 2W_{\min}(0, b) \) and anisotropic region when the earth is (a) on the right side, (b) within and (c) on the left side of the beam. The component of the trapped magnetic field \( H_x \) is positive and the type of daily variation as a function of local time is measured by an instrument on the spinning earth in the absence of the geomagnetic field.

Because of the spin of the earth, a fixed telescope at a low latitude station would scan all directions in the plane of the ecliptic and would thus view during each day the regions where the isotropy of cosmic radiation is disturbed. The intensity measured by the telescope would therefore exhibit a solar daily variation. Taking the walls of the beam along the sun-earth line, \( i.e., \) 12-hour direction and neglecting the influence of the earth's magnetic field, we show in Fig. 3 \( \Delta W_x \) as a function of local time \( T \) on which is dependent the type of daily variation to be expected in each of the three cases. There is an increase of intensity from 12 hours to \( (2\pi - \psi_{\phi}^{\text{dec}})/15 \) hours in Fig. 3 (a'), while a decrease from 00 hours to \( (2\pi - \psi_{\phi}^{\text{dec}})/15 \) hours in
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Fig. 3 (c'). The time of occurrence of the increase in case 3 (a') and the decrease in case 3 (c') is separated by 12 hours. The maximum of the daily variation therefore occurs between 12 and 18 hours irrespective of the relative position of the beam and the earth. When the earth is within the beam, this maximum, as shown by Nagashima,\textsuperscript{11} is shifted towards 12 hours but is still between 12 and 18 hours.

We can summarise the influence of a beam with a positive component of the trapped magnetic field as follows. From the time when the beam is effective while approaching the earth, a region in space in which particles are accelerated is formed and this results in an increase in mean intensity in the afternoon. As the earth enters the beam, a new region of deceleration is created. This region goes on progressively decreasing but with increase in the amount of deceleration produced. The region of acceleration simultaneously increases but with a decrease in the amount of acceleration. The mean intensity therefore progressively decreases and attains its original value at the centre of the beam when both the regions are equal in width. As the earth leaves the beam, the region of acceleration disappears leaving behind a decelerated region and a decrease of mean intensity which returns to its normal value when the beam ceases to be effective.

In Fig. 4 we illustrate all these cases when \( H_z \) is negative, \textit{i.e.}, directed opposite to what has been considered so far. The electric field is now directed from right to left so that in Fig. 4 (a) when the beam is approaching the earth we get a decelerated region from 0 to \( \psi_{b_{\text{sec}}} \) where

\[
\psi_{b_{\text{sec}}} = \cos^{-1} \left( -1 + 2 \sec \phi \frac{\omega_{\text{min}}(0, b)}{\omega} \right) \quad \text{and} \quad \pi > \psi_{b_{\text{sec}}} > 0
\]  

In Fig. 4 (b) there is an accelerated region from \( \psi_x \) to \( \psi_{(b-\pi)} \) and a decelerated region from \( \psi_{(b-\pi)} \) to \( \psi_x \) where

\[
\psi_x = \cos^{-1} \left( -1 + 2 \sec \phi \frac{x \omega_{\text{min}}(0, b)}{\omega} \right) \quad \text{and} \quad \pi > \psi_x > 0
\]  

and

\[
\psi_{(b-\pi)} = \cos^{-1} \left( 1 - 2 \sec \phi \frac{b - x \omega_{\text{min}}(0, b)}{\omega} \right) \quad \text{and} \quad 2\pi > \psi_{(b-\pi)} > \pi
\]

In Fig. 4 (c) when the earth leaves the beam we get an accelerated region from \( \pi \) to \( \psi_{b_{\text{sec}}} \) where

\[
\psi_{b_{\text{sec}}} = \cos^{-1} \left( 1 - 2 \sec \phi \frac{\omega_{\text{min}}(0, b)}{\omega} \right) \quad \text{and} \quad 2\pi > \psi_{b_{\text{sec}}} > \pi
\]
FIG. 4. Deflections of primary particles of energy $\approx 2W_{\text{min}}$ (0, b) and anisotropic region when the earth is (a) on the right side, (b) within and (c) on the left side of the beam. The component of the trapped magnetic field $H_x$ is negative and the type of daily variation as a function of local time is measured by an instrument on the spinning earth in the absence of the geomagnetic field.

The type of daily variation recorded by an instrument on the spinning earth, neglecting the effect of the geomagnetic field, is illustrated in Fig. 4 ($a'$, $b'$, $c'$). When the earth is approaching the beam there is a decrease of intensity from $(2\pi - \psi_{0\infty})/15$ hours to 00 hours and when it leaves the beam there is an increase of intensity from $(2\pi - \psi_{b\infty})/15$ hours to 12 hours. The maximum of daily variation, when various energies of primary radiation are considered, is therefore expected to be between 06 and 12 hours.

The electromagnetic fields of the solar beams thus create anisotropy in the primary radiation which when the trapped magnetic field has a positive component gives rise to a maximum in the daily variation between 12 and 18 hours. With a reversed component of the magnetic field this maximum occurs between 06 and 12 hours. The times of maxima relate to the condition when the bending of the trajectories of cosmic ray particles in the geo-
magnetic field has not been allowed for. In the former case, when the beam is effective we should get an increase of mean intensity followed by a progressive decrease while in the latter case there should be a decrease of intensity followed by an increase.

IV. DIURNAL VARIATION OF MESON INTENSITY PRODUCED BY THE ANISOTROPY OF PRIMARY COSMIC RADIATION

The foregoing analysis gives the nature of the anisotropy that will be created by the electromagnetic fields in solar beams. The observable effect of the anisotropy in terms of a solar daily variation is however measured on cosmic ray secondaries produced by the primaries after they have suffered deflection in the geomagnetic field and interacted with matter in the atmosphere. Since the anisotropy, the deflection in the geomagnetic field as well as the interactions in the atmosphere are dependent on the energy of the primary particles, it is preferable for the purpose of evaluating the daily variation to consider the entire cosmic ray spectrum above the geomagnetic cut off rather than a mean energy of the primary radiation, as is usually done.

When the primary radiation is isotropic the intensity of cosmic radiation \( I(\lambda, h) \) observed at an atmospheric depth \( h \) g./cm.\(^2\) and at geomagnetic latitude \( \lambda \) is given by

\[
I(\lambda, h) = \int_{0}^{\pi/2} \int_{0}^{\pi} \int_{E_{\lambda}}^{\infty} m(E, h, \theta, \alpha) i(E) F(\theta, \alpha) \sin \theta \, d\theta \, d\alpha \, dE
\]

(13)

\( F(\theta, \alpha) \) denotes the sensitive area of a recording apparatus at a zenith angle \( \theta \) and azimuth angle \( \alpha \) and \( E_{\lambda}, \theta, a \) is the corresponding cut-off energy at the geomagnetic latitude \( \lambda \). \( m(E, h, \theta, \alpha) \) and \( i(E) \, dE \) are the overall multiplicity and differential energy spectrum respectively of the primary radiation.

If by the presence of the beams, primary particles of energy \( E \) gain an energy \( \Delta E = \Delta W \) for a certain period of time, the change in the intensity \( dI \) is given by

\[
\Delta I = \int_{0}^{\pi/2} \int_{0}^{\pi} \int_{C_{E}}^{\infty} m(E, h, \theta, \alpha) i(E) \Delta E(T_{E}, \theta, \alpha) F(\theta, \alpha) 
\times \sin \theta \, d\alpha \, d\theta \, dE
\]

(14)

where \( C_{E} = E_{\lambda}, \theta, a \) or \( W_{\text{min}}(\phi, x) \) whichever is greater. The factor \( g(E) \) is introduced to take into account the change in the differential energy spectrum of primary protons due to the additional energy gain and is given by Fonger\(^{18}\) as

\[
g(E) = \frac{1}{1 + E} \left[ \frac{2}{1 - (1 + E)^{-3}} + \beta \right]
\]

where \( \beta = 2.07 \)

(15)
For meson intensity in the lower atmosphere, when \( h > 700 \text{ g./cm.}^2 \), \( m(E, h, \theta, \alpha) \) can be approximated as \( m(E, h) \cos^2 \theta \). The local time \( T_{E, \theta, \alpha} \) refers to the direction of the particle outside the earth's magnetic field. Its relation with the local time \( t_{E, \theta, \alpha} \) on the surface of the earth is given by

\[
T_{E, \theta, \alpha} = t_{E, \theta, \alpha} + \psi_{E, \theta, \alpha}
\]  

where \( \psi_{E, \theta, \alpha} \) is an angle through which a cosmic ray particle of energy \( E \) arriving at a zenith angle \( \theta \) and azimuth angle \( \alpha \) is deflected in the east-west plane (the plane of the ecliptic in the present work) in the earth's magnetic field. These values can be read out from the curves supplied by Brunberg and Dattner. To evaluate the change of intensity at the surface of the earth, \( t_{E, \theta, \alpha} \) in Eq. 14 is replaced by \( t_{E, \theta, \alpha} \). To obtain the diurnal variation, the values of \( \Delta I/I \) are calculated by numerically integrating Eq. 14 at 24 local times, viz., \( t = 00, 01, 02, \ldots, 23 \) hours. For an ionization chamber \( F(\theta, \alpha) = 1 \). For counter telescope it can be evaluated by the formula given by Newell and Pressly.

V. NUMERICAL EVALUATION OF THE NATURE OF THE SOLAR DAILY VARIATION OF MESON INTENSITY

To compare the daily variation of meson intensity produced by the anisotropy of primary cosmic radiation with that observed experimentally, we must first examine some physical characteristics of the beam. The velocity of the ionized matter in the beam can be calculated from the time delay between the visible solar disturbances and the subsequent magnetic disturbances in the earth's magnetic field. A delay of about 24 hours when there is a large magnetic storm following a solar flare, indicates a velocity of 2,000 km/sec., while a delay from two to four days in the case of recurring magnetic disturbances suggest a velocity in the range of 1,000 km/sec. to 500 km/sec. We assume therefore that the velocity of the ionized matter at different times varies between 2,000 km/sec. and 500 km/sec.

The width of the beam is taken as \( \sim 6 \times 10^{14} \) cm. With the synodic period of the sun as 27 days and the earth's orbital radius as \( 1.5 \times 10^{13} \) cm., the earth will situate in the beam for about two days. The value is therefore consistent with inferences from geomagnetic data.

At the present moment there is no method by which we can determine the strength of the magnetic field in the beam. Parker has recently shown that the value of the magnetic field in the beam is very insensitive to the density of the gas at the time of emission and with interplanetary density \( \sim 10^{-21} \text{ g./cm.}^3 \) it should be less than \( 1.4 \times 10^{-4} \) gauss. We assume that its value near the ecliptic varies between \( 2 \times 10^{-8} \) gauss to \( 5 \times 10^{-8} \) gauss. This
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is necessary to produce an anisotropy compatible with experimental determination of the solar daily variation at low latitudes which has an amplitude of 0.3 to 1.0%.

With these values we show in Figs. 5 and 6 the expected daily variation of meson intensity at sea-level, i.e., atmospheric depth \( h = 1030 \text{ g/cm}^2 \) when the earth is just outside the beam and when the earth is within the beam at its centre respectively. For \( m(E, 1030) i(E) \), the values given by Nagashima\textsuperscript{22} using the primary spectrum given by Neher as

\[
i(E) = \frac{0.048}{E^{2/3}(1 + 0.09 E^{4/9})^{3/2}}
\]

are used. The amplitudes and the times of maxima of the Fourier components of the daily variation are given in Table I. It must be emphasized that these values depend upon \( i(E) \, dE \), the differential energy spectrum of the primary radiation and \( m(E, 1030) \), the form of the multiplicity function. Recent evidence by Meyer and Simpson\textsuperscript{23} and Neher\textsuperscript{24} suggests that the differential energy spectrum varies during the course of years and a steeper spectrum than what is now assumed will give rise to larger amplitudes than those given in Table I. The precise value of the multiplicity function which is derived from the experimental determination of the latitude effect can be obtained for primary energies upto 15 Bev. For higher primary energies various authors have extrapolated it with different functions. Since at low latitudes primaries above 15 Bev. only are involved this extrapolation presents uncertainties. Hence the actual values at any time may be different from those given in Table I. However, they are not likely to differ much as to alter the picture presented therein.

An important point that emerges from Figs. 5 and 6 is that while a positive component of the trapped magnetic field within the beam gives rise to a diurnal variation at low latitudes with maximum shortly before noon, the reversal of this component will make the maximum in the daily variation shift to early morning hours. The daily variation in equatorial latitudes should therefore be expected to exhibit maximum either during night at about 03 hours or during day at about 11 hours. Beams emitted at different periods may not have identical characteristics and the time of maximum may vary within an interval of about an hour.

When the earth is at some distance from the beam, the walls of the beam will be inclined to the sun-earth line and the anisotropy in directions lying close to the walls of the beams is not accessible from the earth. The anisotropy of particles having energy near \( W_{\text{max}}(0, b) \) is therefore not observed.
and the observed duration of the anisotropic region decreases. As the beam approaches the earth the accessible region increases, attains a maximum value within the beam and then decreases as the beam recedes from the earth.
Fig. 6. The daily variation of meson intensity measured by an ionization chamber at sea-level in equatorial latitudes when the earth is at the centre of the beam of width $\sim 6 \times 10^{18}$ cm.

The amplitudes of the variation which depends upon the effective duration of the anisotropy increases for a few days, reaches a maximum when the earth is at the centre of the beam and then decreases progressively.
The limit of the region of acceleration or deceleration given by Eqs. 5-12 is expressed with reference to the walls of the beam. Their inclination to the sun-earth line introduces a correction to $T_\theta, a$. If we assume tentatively that the influence of the beam extends up to the time that it is within three days from the earth on either side of it, we have a maximum inclination of about 45° to the sun-earth line. The time of maximum would thus be displaced up to 3 hours on either side of the values indicated in Table I. Hence there should be a group of days when the time of maximum progressively shifts to later hours.

A further factor to be considered is the inclination of the walls of the beam to the sun-earth line due to the radial emission of solar matter from the spinning sun. Chapman and Bartels have shown that the inclination would be by an angle of 12°, 24° and 48°, if the velocity of the matter is 2,000 km./sec., 1,000 km./sec. and 500 km./sec. respectively. The time of maximum would thus be further advanced by $\frac{12}{15}, \frac{24}{15}$ and $\frac{48}{15}$ hours respectively.

It will now be realised that the daily variation observed on individual days will not always resemble the curves shown in Figs. 5 and 6, but these can still serve to represent the average characteristics of the daily variation. Analysis of Huancayo data by Sarabhai et al. showing that the broad features of the daily variation of meson intensity at Huancayo can be explained in terms of the two types of variations, one having maximum at 1100 or 1300 hours and the other having a maximum at 0100 or 0300 hours can now be understood. The time of maximum on individual days will not always be sharply at the values given in Table I but will be grouped round these values. Observations by Sarabhai and Nerurkar on the daily variation of meson intensity at Ahmedabad show similar characteristics.

The 12 monthly mean daily variation of meson intensity exhibits a 22-year cycle of change as observed at Huancayo. If this is due to change in the relative frequency of the variations with day and night maxima from year to year, the average orientation of the trapped magnetic field within beams should also have a similar variation. The most prominent feature on the sun which exhibits a 22-year cycle is the magnetic field associated with active solar regions. Maunder has shown from a separate plot of sunspot areas for each hemisphere that there are comparatively large differences in the sunspot numbers of the two hemispheres as well as their time of maxima. One hemisphere appears to be more active than the other and remains so in the next sunspot cycle even though the reversal of the polarity of the magnetic fields associated with active regions takes place. If there is similar difference in activity between the North and the South hemispheres of the sun for
TABLE I

The per cent. amplitude and the time of maximum of the diurnal component of the daily variation of meson intensity measured by an ionization chamber at sea-level in equatorial latitudes by a beam of solar ionized matter of width $\sim 0.66 \times 10^{13}$ cm.

<table>
<thead>
<tr>
<th>Velocity of the beam $v$ km./sec.</th>
<th>Component of the magnetic field $H_z$ gauss</th>
<th>$W_{\text{min}}(0, b)$ Bev.</th>
<th>When the earth is just outside the beam</th>
<th>When the earth is at the centre of the beam</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>$H_z$ positive</td>
<td>$H_z$ negative</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Ampl. %</td>
<td>Time of maximum</td>
</tr>
<tr>
<td>2000</td>
<td>$5 \times 10^{-6}$</td>
<td>5</td>
<td>0.35</td>
<td>11 24</td>
</tr>
<tr>
<td>1000</td>
<td>$5 \times 10^{-6}$</td>
<td>5</td>
<td>0.18</td>
<td>11 24</td>
</tr>
<tr>
<td>500</td>
<td>$5 \times 10^{-6}$</td>
<td>5</td>
<td>0.09</td>
<td>11 24</td>
</tr>
<tr>
<td>2000</td>
<td>$10^{-5}$</td>
<td>10</td>
<td>0.61</td>
<td>10 48</td>
</tr>
<tr>
<td>1000</td>
<td>$10^{-5}$</td>
<td>10</td>
<td>0.30</td>
<td>10 48</td>
</tr>
<tr>
<td>500</td>
<td>$10^{-5}$</td>
<td>10</td>
<td>0.15</td>
<td>10 48</td>
</tr>
<tr>
<td>2000</td>
<td>$1.5 \times 10^{-5}$</td>
<td>15</td>
<td>0.72</td>
<td>10 28</td>
</tr>
<tr>
<td>1000</td>
<td>$1.5 \times 10^{-5}$</td>
<td>15</td>
<td>0.36</td>
<td>10 28</td>
</tr>
<tr>
<td>500</td>
<td>$1.5 \times 10^{-5}$</td>
<td>15</td>
<td>0.18</td>
<td>10 28</td>
</tr>
<tr>
<td>2000</td>
<td>$2 \times 10^{-5}$</td>
<td>20</td>
<td>0.68</td>
<td>10 36</td>
</tr>
<tr>
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<td>$2 \times 10^{-5}$</td>
<td>20</td>
<td>0.34</td>
<td>10 36</td>
</tr>
<tr>
<td>500</td>
<td>$2 \times 10^{-5}$</td>
<td>20</td>
<td>0.17</td>
<td>10 36</td>
</tr>
</tbody>
</table>

* Values reported at a symposium on Electromagnetic Phenomena in Cosmical Physics, Stockholm (1956) relate to the vertical intensity only.
corpuscular emission, and the coherent magnetic field trapped within the beam is in some way related to the local fields of active solar regions it would be possible to have the 22-year cycle of change in the daily variation of meson intensity.

The amplitude of the daily variation on individual days can be as high as 0.7% for meson intensity as shown in Table I. It may be higher than 0.7% if the energy spectrum of the primaries is steeper. The amplitude averaged over a group of days, however, depends upon the number of days on which the beams are effective as well as the types of beams. Taking this number to be less than half it would be possible to account for the average amplitude of 0.1 to 0.3% for ionization chambers.

With a particular orientation of the magnetic field within the beam, the type of anisotropy and hence the daily variation is similar when the earth is on either side of it or within it. Each type of daily variation is thus expected to occur in groups of days. The recurrence tendency is a natural consequence of the persistence over several solar rotations of an active region responsible for a beam.

From a careful examination of geomagnetic disturbances and their association with solar phenomena in 1952-53, a period of low sunspot activity when the active regions were well defined and well observed, Pecker and Roberts have shown that there is a minimum of geomagnetic activity about three days after the CMP of an active region. There are also definite maxima symmetrically situated at about 3 days from the minimum. They suggest that the solar active regions possess a magnetic field which deflects the ionized matter emitted by the region so that there is a deficiency of emitted matter at solar longitudes radially along the active centre. The ionized matter flows along lines of the magnetic field. At some distance above the centre of activity, the kinetic energy of the ions can be sufficient to overcome the magnetic field so that the guiding effect of the field of the active centre controls the ion flow only near the centre. The angle of aperture of this cone of avoidance may vary with the strength of the magnetic field of the active centre as well as that of the emission. With this picture of emission of ionized matter from the sun, we have in the plane of the ecliptic two beams separated on the average by about 5 to 6 days.

If the component of the trapped magnetic field perpendicular to the plane of the ecliptic is the same in both the beams and the earth is situated between them, it is seen from Figs. 3 and 4 that the earth receives accelerated particles from one beam and decelerated particles from the other. The amplitude of the daily variation can then be about double the values given in
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Table I. If however this component of the magnetic field is different in both the beams, the earth receives accelerated or decelerated particles from each of them. Both types of anisotropies are simultaneously present. The resultant variation depends upon the distance between the two beams as well as the characteristics of them and in some cases it is possible to have a daily variation with two maxima. When the earth is on one side of both the beams, only the adjacent beam is effective and we have the resultant variation with only one maximum. It is thus possible to accommodate on the present model the existence of a daily variation with more than one maximum, such as is reported by Sarabhai and Nerurkar.4

VI. CONCLUSION

The creation of an anisotropy by the presence in the neighbourhood of the earth of beams of solar ionized matter with trapped magnetic fields derived from local fields related to active regions on the sun furnishes a plausible interpretation of several significant features of the daily variation of meson intensity. If one adopts the density and the velocity of ionized matter in the beams consistent with solar relationships of geomagnetic disturbances and assumes a strength of the trapped magnetic field compatible with electrodynamical considerations it is possible to derive a daily variation of meson intensity which, at low latitudes, would have a maximum just before noon or in the early morning. The two types of daily variation would occur in groups of days which would have a tendency of 27-day recurrence. The daily variation could have an amplitude up to 1% on individual days. The amplitude as well as the time of maximum of each type of daily variation would be expected to alter during each group. There would also be a possibility of daily variation with two maxima on some occasions.

The present interpretation does not deal with a permanent anisotropy of cosmic rays about which there is at present little experimental knowledge but which may nevertheless be present to a small degree. On the other hand it attempts to explain the observed features of a highly variable anisotropy in terms of a modulation of the primary cosmic ray intensity. Consequently the changes in the daily variation are linked with day-to-day changes in the daily mean intensity of cosmic radiation. A crucial test of the present interpretation would lie in the study of the correlated behaviour of the changes in the daily variation and in the mean intensity. This examination is in progress.

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**Summary**

The present status of knowledge concerning the daily variation of meson intensity is reviewed. A solar daily variation of a constant nature arising out of a permanent anisotropy in the cosmic radiation has not so far been established and even if it exists it may not exceed a few tenths of a per cent. However a number of features of a solar daily variation of a highly variable character having on the average a time of maximum on individual days either in the early morning or near noon are known. An attempt is therefore made to interpret the occurrence of a variable anisotropy of cosmic rays to which are attributed the principal experimental observations.

Beams of solar ionized matter with a frozen magnetic field derived from a solar dipole field have been earlier suggested to explain abnormal diurnal variation on magnetically disturbed days through an anisotropy in primary cosmic radiation created by them. The present paper considers that the variable anisotropy is due to such beams but the frozen magnetic field is derived from the magnetic field of the active solar regions and bears no preferential orientation in respect to the solar dipole field. With different orientations of the magnetic field in the beam, the component perpendicular to the solar equatorial plane could be reversed in direction. Depending upon the direction of this component, the anisotropy in the primary radiation gives rise to a daily variation at equatorial stations with maximum either in early morning hours or near noon for a group of days. With the strength of this component of the magnetic field in the range $10^{-4}$ to $10^{-6}$ gauss and the velocity of the beam between 500 km./sec. and 2,000 km./sec., the daily variation of meson intensity has amplitudes from 0.3 to 1.5%. The simultaneous presence of two such beams gives rise to double the amplitudes or a daily variation with two maxima.

Some further applications of this concept are discussed.

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