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ANOMALOUS COSMIC-RAY ANISOTROPY AND UNIDIRECTIONAL INTERPLANETARY MAGNETIC FIELD DURING 1954

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ABSTRACT

Observations of the interplanetary magnetic field during solar minimum lead to two important conclusions concerning cosmic-ray modulation: (a) the interplanetary magnetic field does not show any sector structure for a few solar rotations, i.e. the field has polarity away from the sun during this interval, (b) cosmic-ray diffusion in the interplanetary medium is essentially anisotropic for rigidities of the order of 10 GV. If diffusion occurs essentially along the magnetic field lines, the cosmic-ray density is a symmetric function of the helio-latitude, with a minimum in the equatorial plane. There is therefore a cosmic-ray density gradient across the solar equatorial plane and it depends on the size of the modulation region. Only if a unidirectional magnetic field is present and if the earth is outside the symmetry plane of the density function, i.e. the solar equatorial plane, is the gradient detected over a long period as a diurnal variation, with the direction of the maximum perpendicular to the interplanetary magnetic field. During the 1954 solar minimum, from July to September, both conditions occur. When the sector structure in the interplanetary magnetic field disappears, the cosmic-ray gradient is detected as an anisotropy with maximum at 127° W, from the earth-sun direction, lasting for the whole period. This direction is in agreement with the northern position of the earth. From the evaluation of the amplitude of the diurnal variation, the size of the modulation region and the dependence of the diffusion coefficient along $\bar{B}$ on the radial distance from the sun are estimated.

RÉSUMÉ

L'observation du champ magnétique interplanétaire pendant le minimum solaire conduit à deux importantes conclusions relatives à la modulation des rayons cosmiques : (a) le champ magnétique interplanétaire ne montre aucune structure sectorielle pendant quelques rotations du Soleil, c'est-à-dire la polarité du champ est dirigée vers l'extérieur du Soleil pendant cet intervalle; (b) la diffusion des rayons cosmiques dans le milieu interplanétaire est essentiellement anisotrope pour des rigidités de l'ordre de 10 GV. Si la diffusion a lieu essentiellement le long des lignes de champ magnétique, la densité de rayons cosmiques est une fonction symétrique de la latitude

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solaire, avec un minimum dans le plan équatorial. Il y a donc un gradient de densité de rayons cosmiques à travers le plan équatorial solaire, et ce gradient dépend de la grandeur de la région de modulation. Ce n'est seulement lorsque le champ magnétique unidirectionnel est présent et que la Terre se trouve à l'extérieur du plan de symétrie de la fonction de densité — c'est-à-dire du plan équatorial solaire — que le gradient est détecté sur une longue période comme variation diurne, avec la direction du maximum perpendiculaire au champ magnétique interplanétaire. Pendant le minimum solaire de juillet à septembre 1954, ces deux conditions se sont réalisées. Lorsque la structure sectorielle dans le champ magnétique interplanétaire disparaît, le gradient de rayons cosmiques est détecté comme une anisotropie avec un maximum à 127 °W à partir de la direction Terre-Soleil, et ce phénomène dure pendant toute cette période. Cette direction s'accorde avec la position nord de la Terre. A partir de l'évaluation de l'amplitude de la variation diurne, on calcule la grandeur de la région de modulation et la dépendance du coefficient de diffusion le long de $\bar{B}$ vis-à-vis de la distance radiale à partir du Soleil.

1. — INTRODUCTION

The anomalous diurnal variation in the galactic cosmic-ray intensity that occurred during July, August and September 1954, at solar minimum, has recently been re-interpreted by Thomson [1] as a variation of solar origin rather than a sidereal anisotropy as reported by the earlier literature. Thomson suggests as a possible explanation, that this effect is related to a probable lack of sector structure in the interplanetary magnetic field during that interval.

This interesting suggestion can be further developed in the light of the data on the interplanetary magnetic field polarity, pertaining to the 1954 solar minimum, obtained by Svalgaard [2] from high-latitude geomagnetic field observations. These data confirm a lack of sector structure in the period of the detection of the anomalous effect.

Furthermore, the values of the cosmic-ray diffusion coefficients, computed for the last solar minimum (1965) from the magnetic-field power spectra, suggest an anisotropic diffusion, especially along the magnetic field lines in the range of rigidities of the detected cosmic rays. The modulation of cosmic rays that occurs in this condition of anisotropic diffusion and the peculiar behaviour of the interplanetary magnetic field can account for the diurnal effect observed during the 1954 minimum in a simple way. From the observed amplitude of the diurnal variation, it is possible to reach a better understanding of the parameters that characterise the modulation region during solar minima.

2. — POLARITY OF THE INTERPLANETARY MAGNETIC FIELD DURING THE 1954 SOLAR MINIMUM

Recently Svalgaard suggested a temporary disappearance of the sector structure of the interplanetary magnetic field characteristic of periods of solar minimum.

As a consequence of the interaction between interplanetary and geomagnetic fields, a perturbation in the vertical component z of the geomagnetic field near the invariant poles occurs. The sign of the z perturbation depends on the polarity of the interplanetary field. Therefore, since 1926, each day has been classified on the basis of the polarity of the interplanetary field [3] using the geomagnetic data registered at Godhavn (77.5° N invariant latitude). From the inferred sector structure of the interplanetary magnetic field during the last four solar cycles, there is evidence of a predominant positive (away from the sun) magnetic field, lasting for a few solar rotations during each solar minimum.

During 1954, the period of uninterrupted positive interplanetary magnetic field $\overline{B}$ occurred from 6 June to 2 September (11 days are not classified), as shown in Figure 1. Of course, no information on the average direction of $\overline{B}$ at the orbit of the earth is available for this period. It is reasonable, therefore, to assume the idealised Archimedean spiral.

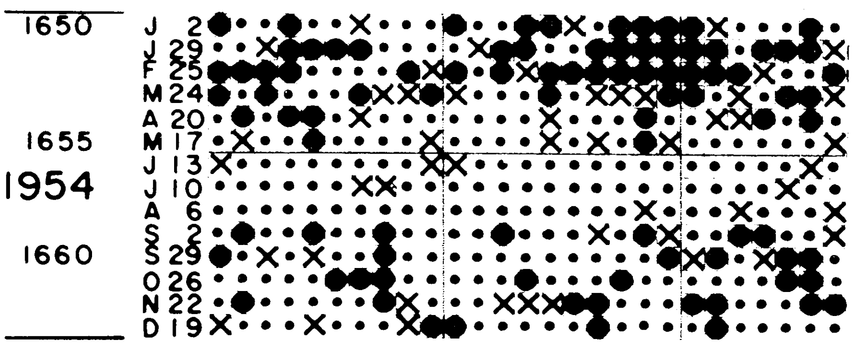

FIG. 1 — The day-to-day polarity of the interplanetary magnetic field during 1954. Large dots indicate negative polarity, small dots positive polarity. Days on which polarity is undetermined are marked by X. (Data obtained by Svalgaard).

3. — OBSERVATIONAL DATA ON THE ANOMALOUS DIURNAL EFFECT DURING 1954

The free-space anisotropy of July-September 1954, evaluated by Thomson [1], is fairly consistent with the presence of a streaming of particles perpendicular to the mean direction of the interplanetary magnetic field. In terms of the cosmic-ray streaming-velocity equation derived by Gleeson [4], under the assumption that the gyro frequency ω is higher than the collision frequency $1/\tau (\omega\tau \gg 1)$, the existence of such a streaming, perpendicular to $\overline{B}$, is explained by the existence of a cosmic-ray density gradient perpendicular to the solar equatorial plane. The sign of the streaming velocity is determined by the polarity of the interplanetary magnetic field. Therefore the persistence of the positive polarity of $\overline{B}$ can account for the constant direction of the anisotropy during the summer of 1954. And the origin of the anisotropy is explained, if the mechanism that builds up the perpendicular gradient is understood.

The average values of the free-space amplitude a and the asymptotic direction φ of the anisotropy, for the period July-September, are $a = 0.39 \pm 0.03\%$ and $\varphi = 127 \pm 6°$ W from the earth-sun direction. These values are computed assuming the primary modulation of intensity $\delta I/I$ to be independent of magnetic rigidity R and effective for $R \leq R_{max} = 30$ GV. Primary modulations of the form $\delta I/I = \beta R$ with $R \leq R_{max} = 30$ GV or $\delta I/I = \beta R^{-1}$ with $R_{max} = \infty$ are less probable. Cosmic-ray intensity data from the neutron monitors of Huancayo, Peru (vertical cut-off rigidity $R_c = 13.45$ GV) and Climax, Colorado ($R_c = 3.03$ GV) and the ionisation chambers of Huancayo, Peru ($R_c = 13.45$ GV), Cheltenham, Maryland ($R_c = 2.09$ GV), Christchurch, New Zealand ($R_c = 2.71$ GV) and Godhavn, Greenland ($R_c = 0.03$ GV) are used.

For relativistic particles, the amplitude a of the free-space anisotropy is related to the bulk streaming velocity u of cosmic rays relative to the earth

$$a = \frac{u}{c}(2+\gamma)$$

$\gamma \sim 2.5$ is the power-law index of the differential rigidity spectrum. Therefore, the detected diurnal effect is due to a streaming velocity $u = 260 \pm 20$ km/sec, with a direction that, to a good approximation, is perpendicular to the idealised spiral field $\overline{B}$. Assuming a co-ordinate system with the x-axis along $\overline{B}$ and the

y-axis perpendicular to $\bar{B}$ in the solar equatorial plane, $\bar{u}$ is along the negative y-axis (Fig. 2). The available observational data on the diurnal variation do not permit an evaluation of a possible component of the streaming velocity perpendicular to the solar equatorial plane, which is therefore neglected.

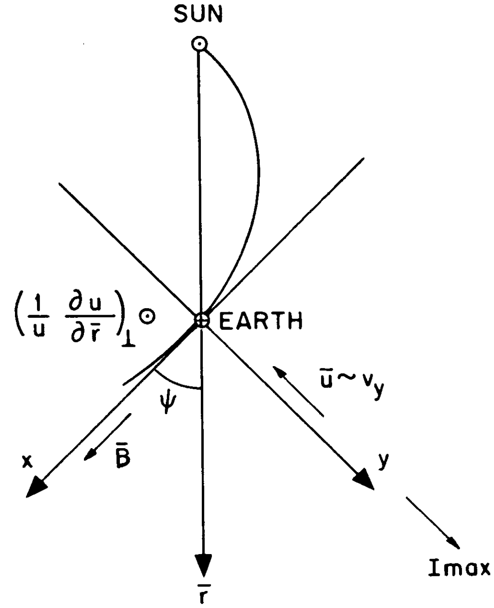

FIG. 2. — The directions of the maximum cosmic-ray intensity I_{max} and streaming velocity $\bar{u}$, in the solar equatorial plane, and the cosmic-ray density gradient perpendicular to $\bar{B}$ (across the solar equatorial plane), responsible for the anisotropy of July-September 1954.

According to Gleeson, to an approximation valid in galactic cosmic-ray modulation problems, the streaming velocity of the cosmic-ray gas is

$$\bar{v} = \bar{v}_{//} + \bar{v}_{\perp} = \left[C(\bar{r}, T)\bar{V} - k\frac{1}{U}\frac{\delta U}{\delta \bar{r}} + C(\bar{r}, T)\frac{\omega\tau}{B}\bar{E} \right]_{//} +$$

$$+ \frac{\omega\tau}{1+(\omega\tau)^2}\left[C(\bar{r}, T)\bar{V} - k\frac{1}{U}\frac{\partial U}{\partial \bar{r}} + C(\bar{r}, T)\frac{\omega\tau}{B}\bar{E} \right] \times \frac{\bar{B}}{B} \qquad (1)$$

since $\omega\tau \gg 1$. U(T) is the density of cosmic rays with kinetic energy T, $\bar{r}$ is the radius vector from the sun, $\bar{V}$ is the solar-wind velocity, $C(\bar{r}, T) \sim 1.5$ is the Compton-

Getting factor for relativistic particles, $k(\bar{r}, \mathrm{T})$ is the diffusion coefficient, ω is the gyro frequency, and τ is the mean collision time in the interaction between cosmic rays and magnetic inhomogeneities. $\overline{\mathrm{E}} = -\overline{\mathrm{V}} \times \overline{\mathrm{B}}$ is the electric field caused by the solar wind in a system of reference fixed at the earth. The effects of collisions $\mathrm{C}(\bar{r}, \mathrm{T})\overline{\mathrm{V}}$, the density gradient $\partial\mathrm{U}/\partial r$ and the electric field $\overline{\mathrm{E}}$ are explicitly represented in the velocity-vector components parallel and perpendicular to $\overline{\mathrm{B}}$.

From the comparison with the experimental estimate of the streaming velocity $\bar{u}$, it follows that $\bar{v}$ lies in the equatorial plane. Furthermore, $v_{//} = v_x = 0$ and $v_\perp = v_y \simeq u$ with $v_y < 0$, since the observed streaming of cosmic rays is approximately perpendicular to $\overline{\mathrm{B}}$ and points eastwards.

In consequence of Equation (1), the transverse streaming velocity $v_\perp = v_y < 0$ has to be associated with a cosmic-ray density gradient $(1/\mathrm{U})$ $(\partial\mathrm{U}/\partial\bar{r})$ across the equatorial plane, pointing northwards, since $\overline{\mathrm{B}}$ is steadily directed away from the sun. Obviously, in the presence of a normal magnetic-field-sector structure, such a gradient could not be detected as an average diurnal effect over periods of the order of a solar rotation, because v_y would change sign when the polarity of $\overline{\mathrm{B}}$ changed. If magnetic irregularities are present, the electric field $\overline{\mathrm{E}}$ can cause a streaming perpendicular to $\overline{\mathrm{B}}$ too, but in this case $v_y > 0$ and the sign of v_y does not change with the polarity of $\overline{\mathrm{B}}$.

4. — MODULATION DUE TO ANISOTROPIC DIFFUSION AND PERPENDICULAR COSMIC-RAY DENSITY GRADIENT

At this point the problem of the physical origin of the perpendicular density gradient (established experimentally) arises. Since a sidereal origin for the anomalous effect has been rejected on the basis of the re-evaluation of the data, the explanation has to be found in the modulation process.

In discussing the modulation mechanism, the results of the interplanetary magnetic-field observations in the period around the year 1965, the last solar minimum, will be considered as a good approximation for the 1954 minimum conditions. From the results of Simpson and Wang [5], the measured levels of galactic cosmic-ray intensity during the two periods of minimum modulation, 1954 and 1965, are equal to within $\pm 0.5\%$.

Jokipii and Coleman [6] analysed the magnetic-field power spectra calculated from the data obtained with the Mariner IV magnetometer during late 1964 near the earth's orbit. They determined the cosmic-ray diffusion tensor for interplanetary space. For particles with rigidity R > 1 GV, the parallel and perpendicular cosmic-ray diffusion coefficients with respect to the field direction are

$$k_{//} \sim 1.5 \times 10^{21}\ \mathrm{R}^2 \beta\ \mathrm{cm}^2/\mathrm{sec}$$
$$k_{\perp} \sim 4 \times 10^{21}\ \beta\ \mathrm{cm}^2/\mathrm{sec}$$

with $\beta = w/c \sim 1$ (w = particle velocity). Diffusion perpendicular to the field direction is determined essentially by the random walk of the magnetic lines of force [7].

The rate $k_{\perp}/k_{//} \sim \mathrm{R}^{-2}$ indicates that, for rigidity $\mathrm{R} \gtrsim 10$ GV, the diffusing particles are tied to the magnetic field lines during their path and the diffusion is anisotropic.

Considering the uncertainty in determining the rigidity range of the primary modulation, a mean primary rigidity of approximately 10 GV is assumed in the discussion of the effect, since the diurnal variation is detected with maximum amplitude by the Climax neutron monitors, which respond to a mean rigidity $\overline{\mathrm{R}} = 12$ GV.

The interesting consequence of such an anisotropic diffusion of cosmic rays is that the modulation in the solar system, and therefore the cosmic-ray density U(T), depends on helio-latitude [8, 9].

The quasi-static approximation of the transport equation of cosmic rays in the interplanetary medium, for a spherically symmetric solar wind, is

$$\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 k_{rr}\frac{\partial \mathrm{U}}{\partial r}\right) + \frac{1}{3r^2}\left[\frac{\partial}{\partial r}(r^2 \mathrm{V})\right]\frac{\partial}{\partial \mathrm{T}}(\alpha\, \mathrm{TU}) - \frac{1}{r^2}\frac{\partial}{\partial r}(r^2 \mathrm{VU}) = 0 \qquad (2)$$

$\alpha(\mathrm{T}) = (\mathrm{T} + 2\mathrm{T}_0)/(\mathrm{T} + \mathrm{T}_0) \simeq 1$, for relativistic particles ($\mathrm{T}_0 = m_0 c^2$, the rest energy of the cosmic-ray particle). The diffusion coefficient k_{rr} along the radius vector $\bar{r}$ is a linear combination of $k_{//}$ and $k_{\perp}$:

$$k_{rr} = k_{//} \cos^2\psi + k_{\perp} \sin^2\psi \qquad (3)$$

ψ is the angle between the radius vector $\bar{r}$ and the outward direction along the magnetic field [10].

In the limit $r\mathrm{V} \ll k_{rr}$ ($r\mathrm{V} \simeq 10^{20}$ cm^2/sec at the earth's orbit and $k_{rr} \simeq 10^{23}$ cm^2/sec for particles of R ~ 10 GV), the transport equation (2) has been solved by Jokipii [10], following an approach similar to that used by Axford and Gleeson [11]:

$$\mathrm{U}(r, \mathrm{T}) \simeq \mathrm{U}_{\infty}(\mathrm{T})\left(1 - \frac{2+\alpha\gamma}{3}\int_{r_e}^{\mathrm{D}} \frac{\mathrm{V}}{k_{rr}}\, dr\right) \qquad (4)$$

γ is the index of the differential rigidity spectrum, $U_{\infty}(T)$ the unmodulated cosmic-ray density, D the boundary of the solar modulation region, and r_e the sun-earth distance. For relativistic particles, $q=(2+\alpha\gamma)/3 \simeq 1.5$.

For the condition of anisotropic diffusion, $k_{\perp}$ is neglected,

$$k_{rr} \simeq k_{//} \cos^2 \psi \tag{5}$$

where the angle ψ is related to the polar angle $\theta(\theta=\pi/2-\lambda$, where $\lambda=$ helio-latitude) by $\psi=\tan^{-1}(r\Omega \sin\theta/V)$; $\Omega \simeq 3\times10^{-6}$ rad/sec is the solar angular velocity. The diffusion coefficient can therefore be expressed as a function of the helio-latitude λ as

$$k_{rr} \simeq k_{//} \frac{V^2}{V^2+\Omega^2 r^2 \cos^2\lambda} \tag{6}$$

and the modulation is also latitude-dependent. Assuming V and $k_{//}$ to be independent of $\bar{r}$ inside the modulation region, and substituting Equation (6) in the transport equation (4),

$$U(r,\, T) = U_{\infty}(T)\left[1 - \frac{q}{k_{//}} \int_{r_e}^{D} \left(V + \frac{\Omega^2 r^2 \cos^2\lambda}{V}\right) dr\right] \tag{7}$$

Because of the diffusion along $\overline{B}$, the cosmic-ray density is reduced more than in the case of isotropic diffusion. The reduction term $F(\lambda,\, D)$ at the orbit of the earth is

$$F(\lambda, D) = U_{\infty}(T)\, q\Omega^2 \frac{\cos^2\lambda}{3k_{//}V}(D^3 - r_e^3) \tag{8}$$

$F(\lambda,\, D)$ is latitude-dependent, with a maximum in the equatorial plane $\lambda=0$. Therefore $U(\bar{r},\, T,\, \lambda)$ has a minimum in the equatorial plane and increases symmetrically with distance above and below it. It is important to note that the reduction term depends on the size D of the modulation region.

The anisotropic diffusion therefore implies a cosmic-ray density gradient that at the orbit of the earth is

$$\frac{1}{U}\frac{\partial U}{\partial z} = \frac{1}{U}\frac{\partial U}{\partial \lambda}\frac{\partial \lambda}{\partial z} \simeq \frac{q\Omega^2(D^3-r_e^3)}{3k_{//}vr_e} \sin(2\lambda)\cos^2\lambda \tag{9}$$

$(\partial\lambda/\partial z)=\cos^2\lambda/r_e$ since $z/r_e=\tan\lambda$, the z-axis is perpendicular to the solar equatorial plane, pointing northward. The gradient is zero when $\lambda=0$, northward when $z>0$ (in the northern hemisphere) and southward when $z<0$ (in the southern hemisphere), because of the symmetry of the cosmic-ray density $U(\bar{r},\, T,\, \lambda)$.

5. — ESTIMATE OF THE BOUNDARY D AT SOLAR MINIMUM

Provided that the average heliographic latitude of the earth during the period July-September is $\lambda_0 \sim 6°$ N, the cosmic rays detected come from the northern hemisphere, where a northward gradient exists. In fact the helio-latitude $\lambda_0 \sim 6°$ N corresponds to an average earth–solar-equatorial-plane distance $z_e \sim 0.15 \times 10^{13}$ cm. The gyro radius ρ of a particle of rigidity $R \sim 10$ GV, in a typical field $|\overline{B}| \sim 4\gamma$, is $\rho = 0.8 \times 10^{12}$ cm. Therefore ρ is contained in $z_e (\rho < z_e)$ and the guiding centres of the particles belong to the northern hemisphere. Thus, detectors register a maximum in intensity perpendicular to $\overline{B}$ in the morning hours, due to particles with guiding centres at maximum z (highest density detectable), since the polarity of the magnetic field is positive. The minimum intensity is detected in the opposite direction and it is due to low-latitude cosmic-ray density (note that the guiding centres of the particles with $R \gtrsim 20$ GV, detected in the minimum-intensity hours, belong to the southern hemisphere, where the gradient is reversed; however, the direction of maximum intensity does not change).

The amplitude of the diurnal variation detected is related to the cosmic-ray density, in that

$$a = \frac{1}{2}\left(\frac{1}{U}\frac{\partial U}{\partial z}\right)_0 \Delta z = \frac{q(D^3 - r_e^3)\Omega^2 \sin(2\lambda_0)\cos^2\lambda_0}{3k_{//}Vr_e}\rho \qquad (10)$$

$\Delta z = 2\rho$, ρ is the Larmor radius and $(1/U\ \partial U/\partial z)_0$ is the cosmic-ray gradient computed for $\lambda_0 \sim 6°$ N. Therefore the estimation of a ($a = 0.39\%$) leads to determination of the parameter D during solar minimum, since the other parameters of Equation (10) are known. The average magnetic-field magnitude is $|\overline{B}| = 4.12\ \gamma$ (Mariner IV data); the solar-wind velocity is $V = 400$ km/sec, detected at the 1965 solar minimum [12]. Under these conditions, the depth of the modulation region is estimated to be $D \simeq 6$ AU. This value is in agreement with the estimate of Simpson and Wang [5] for the residual modulation during 1954 and 1965. Considering the phase lag Δt between solar activity and cosmic-ray modulation at solar minimum, they deduce an upper limit for the boundary $D \sim 5$–10 AU. If a dependence of the diffusion coefficient on the radial distance r is assumed, $k_{//} = k_{0//}(r/r_e)^l$ (with $k_{0//} = 1.5 \times 10^{23}$ cm^2/sec for particle rigidity $R \sim 10$ GV), a deeper modulation region is required to build up the same cosmic-ray density gradient and therefore the same anisotropy. In fact, the particles need a longer path along the field lines to undergo the same degree of modulation, if the diffusion becomes less effective for larger values of r. When the index $l=1$ is assumed, $D \sim 10$ AU is still compatible with the estimate by Simpson and Wang; when $l=2$, $D \sim 50$ AU. The radial dependence of the diffusion coefficient along $\overline{B}$ can therefore be assumed to be $k_{//} \propto r^l$, with $l=0, 1$.

6. — CONCLUSIONS

It is interesting to point out that during 1965, the last solar minimum, there is again evidence for a lack of sector structure during the period 4 March–11 April, while at the same time the earth was out of the solar equatorial plane. The two conditions for the detection of the cosmic-ray density gradient (1/U) $(\partial U/\partial z)$ across the solar equatorial plane are therefore satisfied again. During March-April, the earth was south of the equatorial plane and the detectors registered a southward gradient of cosmic particles. In consequence of Equation (1), cosmic-ray streaming should exist, but opposite to the direction observed during 1954 (namely $v_y > 0$ and maximum intensity in the afternoon). Such an anisotropy is not easily resolved from the co-rotation anisotropy.

The description of the effect that occurred during the 1954 minimum is therefore in agreement with the fact that no anomalous diurnal variation was observed in the intensity of galactic cosmic rays during 1965.

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REFERENCES

[1] D. M. THOMSON. — The solar diurnal variation of cosmic rays at the 1954 solar minimum. *Planet. Space Sci.*, **19**, 1169 (1971).
[2] L. SVALGAARD. — Interplanetary magnetic-sector structure 1926–1971. *J. Geophys. Res.*, **77**, 4027 (1972a).
[3] L. SVALGAARD. — Interplanetary magnetic-sector structure 1926–1971. Dan. Meteorol. Inst., Geophys. Pap. 29, 1972b.
[4] L. J. GLEESON. — The equations describing the cosmic-ray gas in the interplanetary region. *Planet. Space Sci.*, **17**, 31 (1969).
[5] J. A. SIMPSON and G. R. WANG. — The eleven-year and residual solar modulation of cosmic rays. *Astrophys. J.*, **161**, 265 (1970).
[6] J. R. JOKIPII and P. J. COLEMAN Jr. — Cosmic-ray diffusion tensor and its variation observed with Mariner IV. *J. Geophys. Res.*, **73**, 5495 (1968).
[7] J. R. JOKIPII and E. N. PARKER. — Stochastic aspects of magnetic lines of force with application to cosmic-ray propagation. *Astrophys. J.*, **155**, 777 (1969).
[8] E. N. PARKER. — The passage of energetic charged particles through interplanetary space. *Planet. Space Sci.*, **13**, 9 (1964).
[9] J. J. QUENBY and B. LIETTI. — The second harmonic of the cosmic ray daily variation. *Planet Space Sci.*, **16**, 1209 (1968.
[10] J. R. JOKIPII. — Cosmic-ray propagation in the solar wind. *Rev. Geophys. Space Phys.*, **9**, 27 (1971).
[11] L. J. GLEESON and W. I. AXFORD. — The solar radial gradient of galactic cosmic rays. *Can. J. Phys.*, **46**, S937 (1968).
[12] J. T. GOSLING and R. T. HANSEN. — Solar wind speed distributions. *J. Geophys. Res.*, **76**, 1811 (1971).