PAPER 42

SOLAR COSMIC RADIATION AND THE INTERSTELLAR MAGNETIC FIELD*

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ABSTRACT

The increase of cosmic radiation on 23 February 1956 by solar radiation exhibited in the first minutes a high peak at European stations that were lying in direct impact zones for particles coming from a narrow angle near the sun, whilst other stations received no radiation for a further time of 10 minutes and more. An hour later all stations in intermediate and high latitudes recorded solar radiation in a distribution as would be expected if this radiation fell into the geomagnetic field in a fairly isotropic distribution. The intensity of the solar component decreased at this time at all stations according to the same hyperbolic law ($\sim t^{-2}$).

It is shown, that this decreasing law, as well as the increase of the impact zones on the earth, can be understood as the consequence of an interstellar magnetic field in which the particles were running and bent after their ejection from the sun.

Considering the bending in the earth's magnetic field, one can estimate the direction of this field from the times of the very beginning of the increase in Japan and at high latitudes. The lines of magnetic force come to the earth from a point with astronomical co-ordinates near 12·00, 30° N. This implies that within the low accuracy they have the direction of the galactic spiral arm in which we live. The field strength comes out to be about $0 \cdot 7 \times 10^{-6}$ gauss. There is a close agreement with the field, that Fermi and Chandrasekhar have derived from Hiltner's measurements of the polarization of starlight and the strength of which they had estimated to the same order of magnitude.

I. OBSERVATIONS

A comparison of a number of neutron recordings on 23 February 1956 is given in Fig 1 with data by A. E. Sandström [1] for Stockholm, R. B. Brode and A. Goodwin [2] for Berkeley, P. Meyer and J. A. Simpson [3] for Chicago, C. D. Rose and J. Katzmann [4] for Ottawa, P. L. Marsden, J. W. Berry, P. Fieldhouse and J. G. Wilson [5] for Leeds, B. Meyer [6] for Göttingen,

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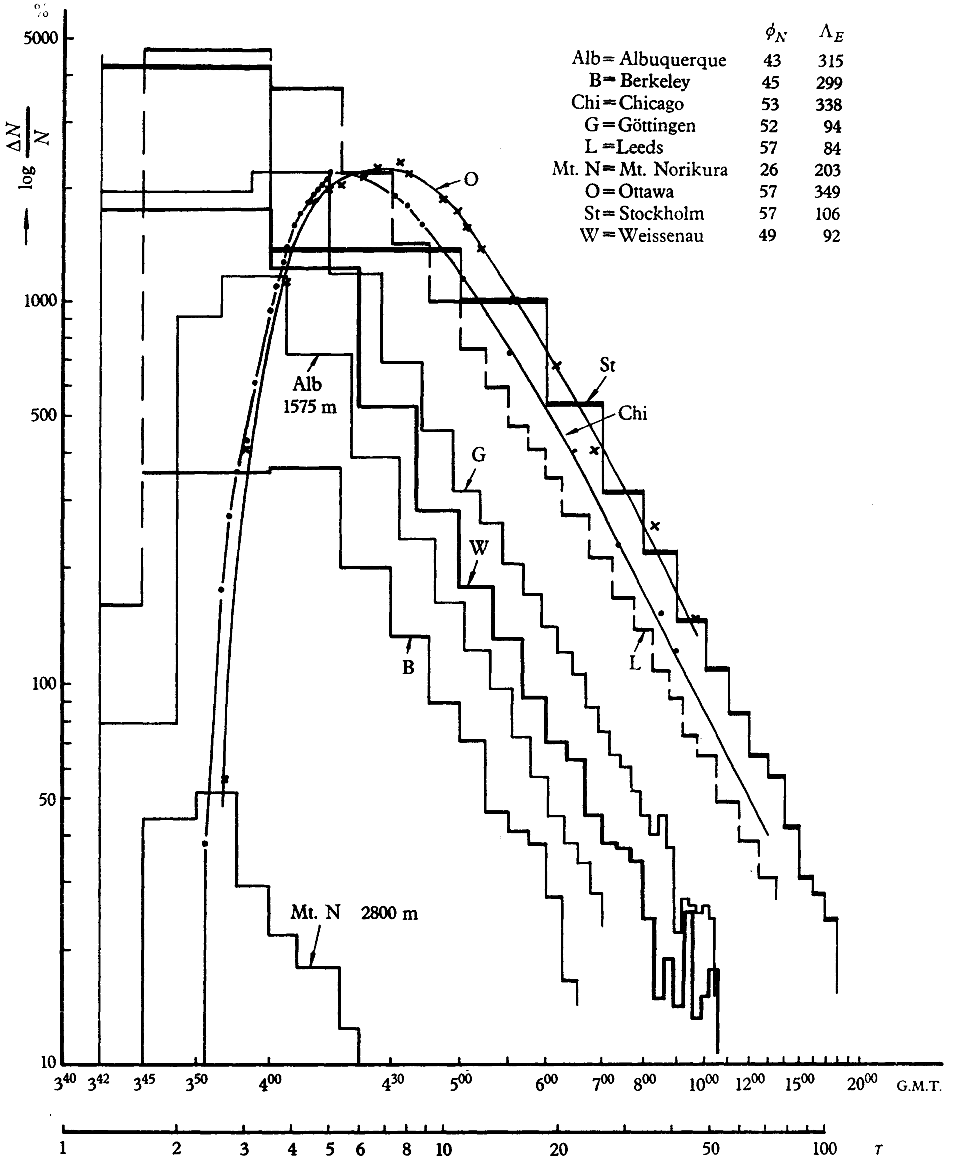

Fig. 1. Neutron records on 23 February 1956.

A. Ehmert and G. Pfotzer [7] for Weissenau, R. Brown [8] for Albuquerque, Y. Sekido and C. Ishii [9] for Mount Norijura. A logarithmic scale is used for the relative increase $\Delta N/N$ of neutron intensity as a function of the time t which is counted from 3.32 G.M.T. The values of $\tau = t/8{\cdot}3$ min count this time in manifolds of the time that light needs to travel from the sun to the earth. At later times all curves decrease very nearly in proportion to t^{-2}. The European stations with the earliest beginning of the increase (3·42 G.M.T. $\tau = 1{\cdot}2$) are the first to reach the state of the decreasing law. Others, lying out of the direct impact zones reach this state considerably later.

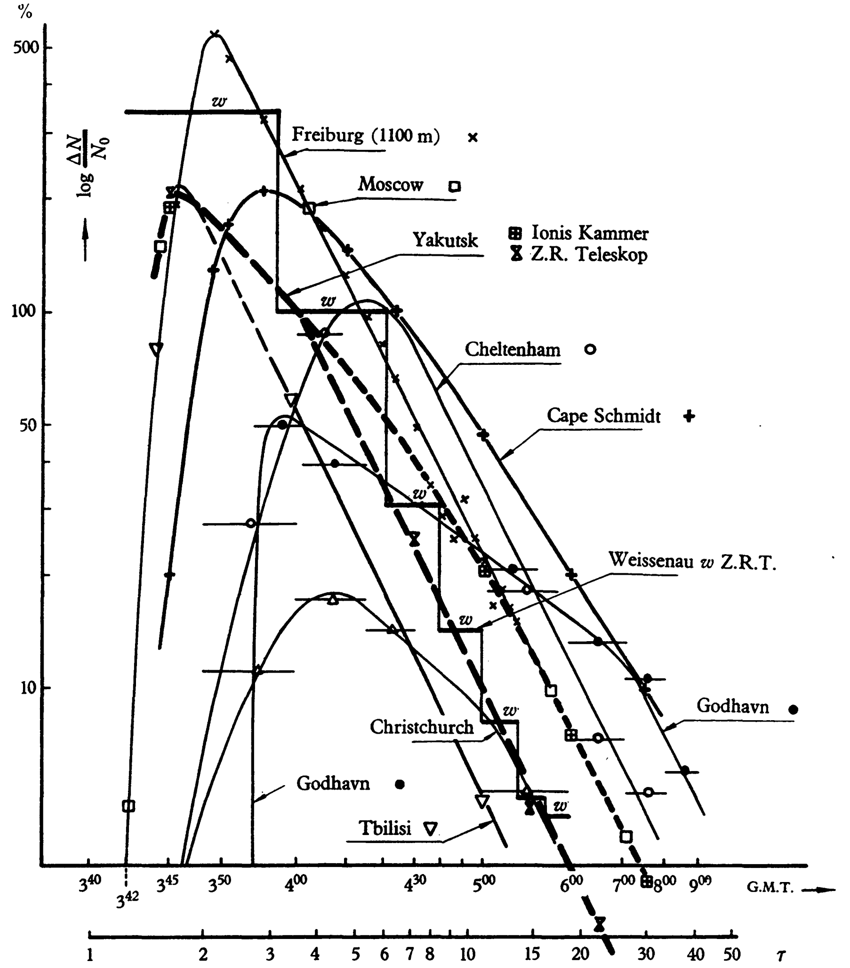

Fig. 2. Ionization records on 23 February 1956.

The same is demonstrated in Fig. 2 by the comparison of some records by ionization chambers with data given by A. Sittkus [10] for Freiburg and S. E. Forbush [11] for Christchurch, Godhavn and Cheltenham and by Vernov, Kopilov, Dorman and Shafer [12] for Moscow, Yakutsk and Tbilisi.

The same character of the curves holds also for earlier cases as is shown by Fig. 3 giving an adequate representation of Forbush's data [13].

We intend to verify, that the characteristic features of this material, i.e. the differences in the times of onset of the increases at different stations

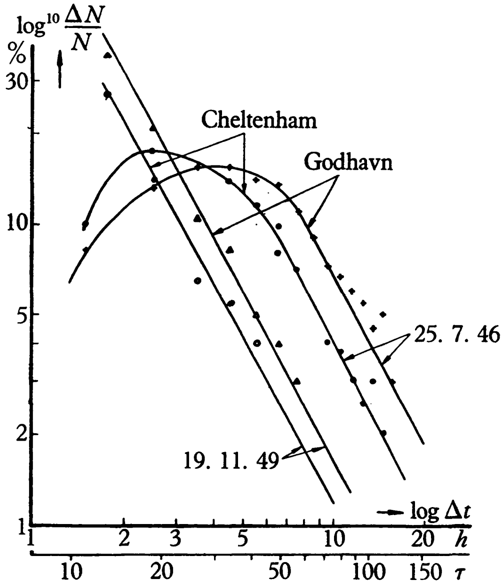

Fig. 3. Ionization records on 19 November 1949.

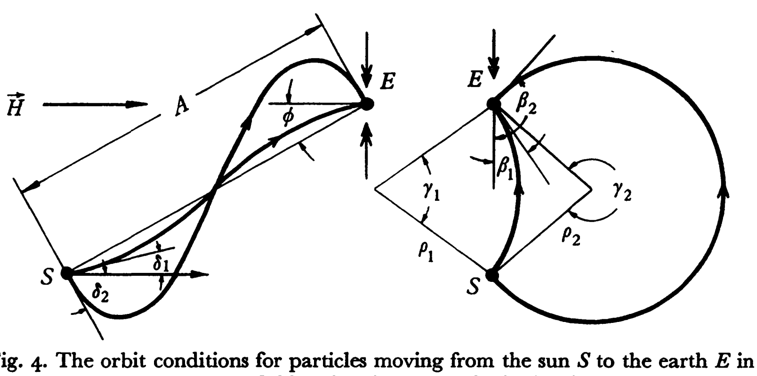

Fig. 4. The orbit conditions for particles moving from the sun S to the earth E in a magnetic field **H** forming an angle ϕ with SE.

and the general decreasing law, can be explained by the action of an interstellar field bending of the orbits of the solar particles.

Suppose, that at the time $t=0$ there are N_0 particles starting from the sun (denoted by S in Fig. 4) which are distributed isotropically in all directions and spiral along and around the magnetic lines of force. They all move in the relativistic region of energy with nearly the same velocity.

Without the magnetic field a receiver at the point E would in a short time record $N_0/4\pi A^2$ particles/cm^2 at the time $t_0 = A/\beta_1 c$.

With the field present at later times $t > t_0$ particles can arrive at the earth E having run along a spiral orbit of the length

$$L = \beta_1 ct; \quad \beta_1 = \frac{v}{c}, \tag{1}$$

They arrive from other directions than from that of the sun. We define the direction of the orbits hitting E by the two angles β and δ of the projection of the orbit as defined by Fig. 4. Two different orbits are drawn in this figure. We can also use β together with the angle α between the orbit and the magnetic field. α is constant throughout the orbit.

The condition for an orbit to hit E is

$$\frac{A \cos \phi}{\beta_1 c . \cos \alpha} = \frac{pc \sin \alpha . \delta}{\beta_1 c \sin \alpha . c\mathrm{H}} . \operatorname{arc} \sin \frac{A \sin \phi \, eH}{2pc \sin \alpha}, \tag{2}$$

where the time for propagation along the field has been put equal to the time for propagation normally to the field.

A is the distance between S and E. As

$$\frac{A \cos \phi}{\beta_1 c \cos \alpha} = t \tag{3}$$

and using

$$\tau = \frac{t}{t_0} \tag{4}$$

we get

$$\tau = \frac{\cos \phi}{\cos \alpha}; \quad \sin \alpha = \left[1 - \left(\frac{\cos \phi}{\tau} \right)^2 \right]^{\frac{1}{2}}. \tag{5}$$

Furthermore, we write

$$\epsilon = \frac{pc}{p_1 c} \quad \text{with} \quad p_1 c = eHA, \tag{6}$$

where for high energies ϵ is a measure of the particle energy. Eq. (2) now gets the form

$$\frac{\tau}{2\epsilon} = \operatorname{arc} \sin \frac{\sin \phi}{2\epsilon \sin \alpha} \tag{7}$$

and

$$\sin \frac{\tau}{2\epsilon} = \left\{ \frac{\sin \phi}{2\epsilon \sqrt{\left[1 - \left(\frac{\cos \phi}{\tau} \right)^2 \right]}} \right\}_{\tau \gg \cos \phi} \longrightarrow \frac{\sin \phi}{2\epsilon}. \tag{8}$$

This is the impact condition connecting τ, ϵ and ϕ. Fig. 5 illustrates Eq. (8) for $\phi = 30°$. A part of the various types of orbits are drawn and numbered as well as the corresponding branches of $\epsilon(\tau)$.

From Fig. 4 it is immediately seen that

$$\beta = \tfrac{1}{2}\delta = \tfrac{1}{2} \text{ arc sin } \frac{A \sin \phi \, eH}{2pc \sin \alpha}, \tag{9}$$

and with (6) and (7)

$$\beta = \tau/2\epsilon. \tag{10}$$

Finally, we have

$$tg\delta = \cos \beta \; tg\alpha = \cos\left(\frac{\tau}{2\epsilon}\right) . \left[\left(\frac{\tau}{\cos \phi}\right)^2 - 1\right]^{\frac{1}{2}}, \tag{11}$$

and for $\tau \gg \cos \phi$

$$tg\delta \to \tau . \frac{\cos(\tau/2\epsilon)}{\cos \phi}. \tag{12}$$

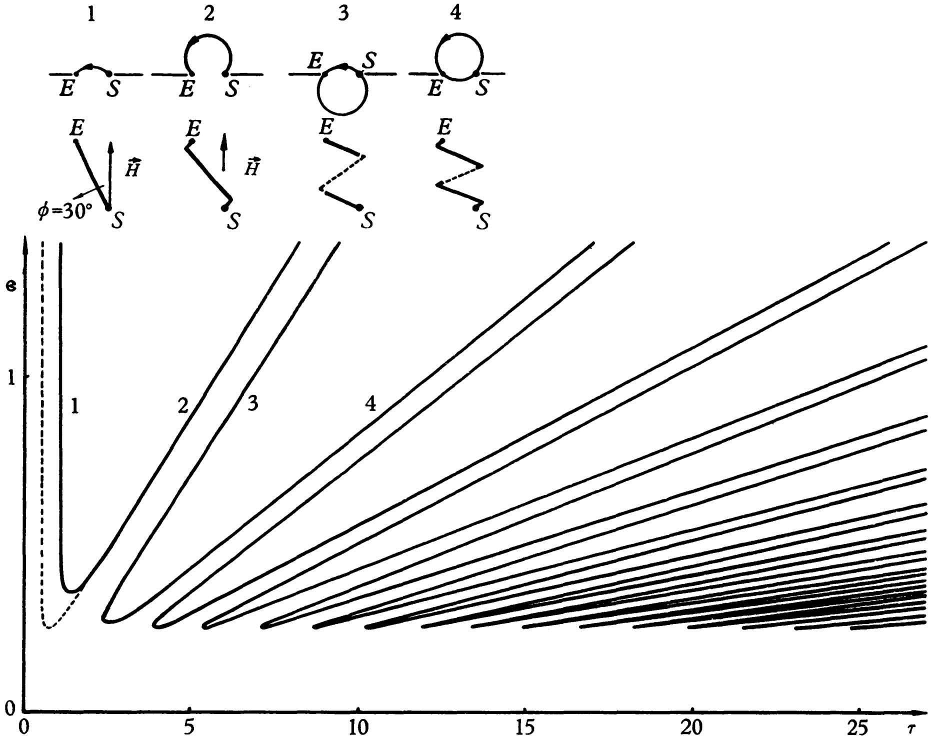

Fig. 5. $\epsilon(\tau)$ for $\phi = 30°$. The dashed line results if $\sin \alpha$ is neglected.

Fig. 6 gives the apparent source in the sky for $\phi = 30°$. H denotes the direction of the field (the lines coming to the earth) and S the direction to the sun. The angular distance from the direction of H at the sky equals α in Eq. (2) and is connected with τ by Eq. (5). The later branches are not fully drawn in. Setting the beginning of ejection at 3.32 G.M.T., we have written at the first branch the times in G.M.T. as calculated from the values of τ.

For $(2n-1)\,\pi \leqslant \beta \leqslant 2n\pi$ (with $n = 1, 2, 3, \ldots$) the values of β calculated from Eq. (10) must be subtracted by π to give the correct value. In this equation the curves are to be read in the reverse direction in these cases. Besides $\alpha(\tau)$ also $\beta(\tau)$ and $\delta(\tau)$ are given in Fig. 7, all for the case $\phi = 30°$. S denotes the direction to the sun. Particles with very high magnetic rigidity can arrive from here when $\tau = 1$. But in a short time complete deviation dominates and it is very striking, that particles with higher energy are restricted to the neighbourhood of $\delta = \pm 90°$, $\beta = 0°$ or $180°$. These directions normal to the field lines are marked in Fig. 4 by double-arrows.

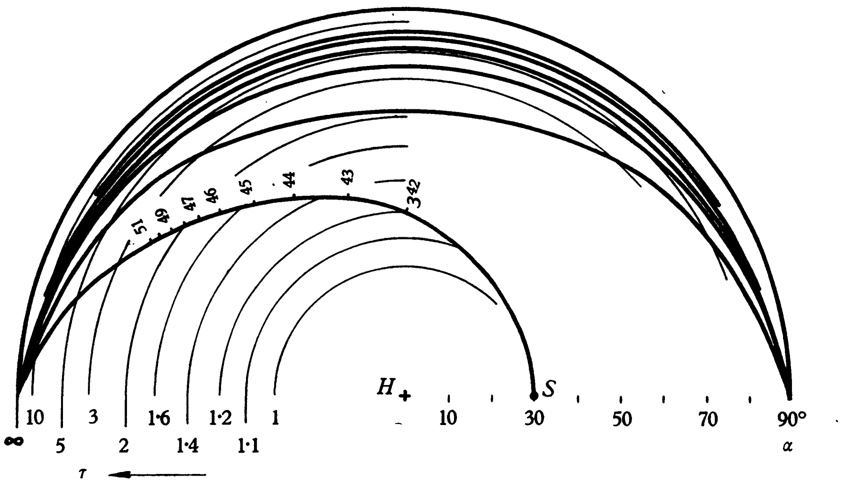

Fig. 6. Variation of the apparent source in the sky from S to ∞. The marks from 3^{42} to 3^{51} refer to time instants on 23 February 1956.

There exists a minimum energy, depending on ϕ;

$$\epsilon_{\min} = \left\{ \frac{\sin\phi}{2\left[1-\left(\frac{\cos\phi}{\tau}\right)^2\right]^{\frac{1}{2}}} \right\} \xrightarrow[\tau \gg \cos\phi]{} \tfrac{1}{2}\sin\phi. \tag{13}$$

At higher values of τ all possible values of δ and of β are continuously allowed, especially if we assume that the emission lasts over perhaps 10 min. This broadens the lines in Fig. 7 in the direction of τ to overlapping bands. With growing τ the angle α approaches $90°$; this implies that particles finally come in the plane normal to **H** within a range of $180°$. This is sufficient to ensure an impact zone for all stations if a suitable direction of the field is assumed. For $\phi = 0$, that means that the field has the direction from the sun to the earth, and at high τ all directions in the plane normal to the field are allowed.

We do not know the direction of the field and try to find it from the following observations:

(1) Godhavn and Resolute have observed an impact. This is only possible if the direction of **H** is to the north of the sun.

(2) The first beginning of the increase varied with geomagnetic co-ordinates of the station. We use the stations with continuous reading. They are listed in Table 1.

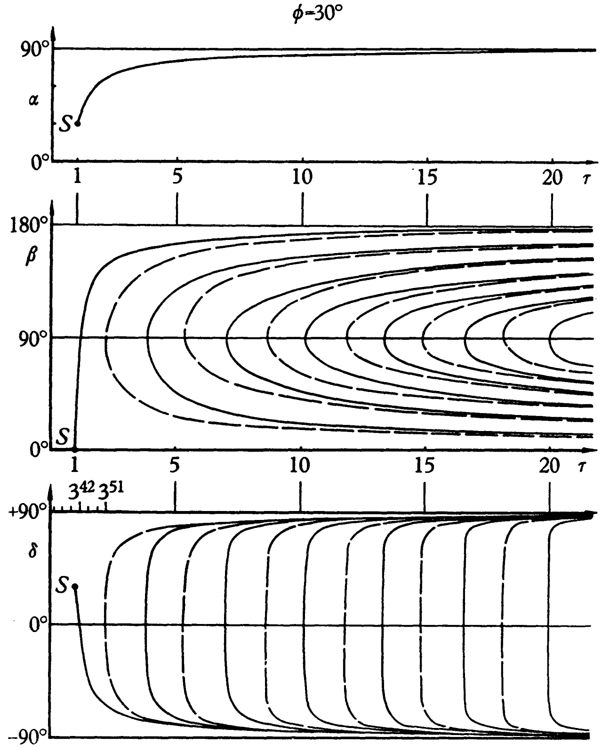

Fig. 7. $\alpha(\tau)$, $\beta(\tau)$ and $\delta(\tau)$ for $\phi = 30°$.

In Fig. 8 these times are plotted by full circles against the geomagnetic latitude. The dispersion of the points indicates an influence of the longitude. Assuming the same coefficient

$$K_{\tau,\phi} = \frac{\Delta t}{\Delta\phi} = \frac{1 \text{ min}}{4°} \tag{14}$$

for all geomagnetic longitudes as indicated by the lines in Fig. 8 we get the distances of these lines in good proportion to the differences of the longitude of the respective stations with exception of Norikura, Yakutsk, and Swerdlowsk and perhaps C. Schmidt.

These stations had, according to this system, to begin before 3.42 G.M.T. They all began at the same time, when the first particles reached the earth. Only Norikura had special conditions and therefore had a later beginning.

The times of the other stations' beginning, reduced for 50° northern geomagnetic latitude with the coefficient of Eq. (14), fit well in a line of dependence on the geomagnetic longitude of these stations. With another

Table 1. *Geomagnetic stations with continuous reading*

	ϕ geom.	Λ geom.	G.M.T.	Observer	Method
Freiburg	49°	90°	3·42	Sittkus[10]	Ionization
Cheltenham	50°	350°	3·48	Forbush[11]	Ionization
Godhavn	79°	32°	3·53	Forbush[11]	Ionization
Moscow	52°	123°	3·42	Vernov, Kopilov	Ionization
Swerdlowsk	48°	141°	3·42	Dorman and Shafer[12]	Ionization
Yakutsk	51°	195°	3·42		Ionization
C. Schmidt	63°	180°	3·42		Ionization
Leeds	57°	84°	3·43–3·45	Marsden, Berry, Fieldhouse and Wilson[5]	Ionization
Chicago	53°	338°	3·50	Meyer and Simpson[3]	Neutrons
Mt. Norikura	26°	208°	3·45	Sekido, Ishii and Migazaka[9]	Neutrons

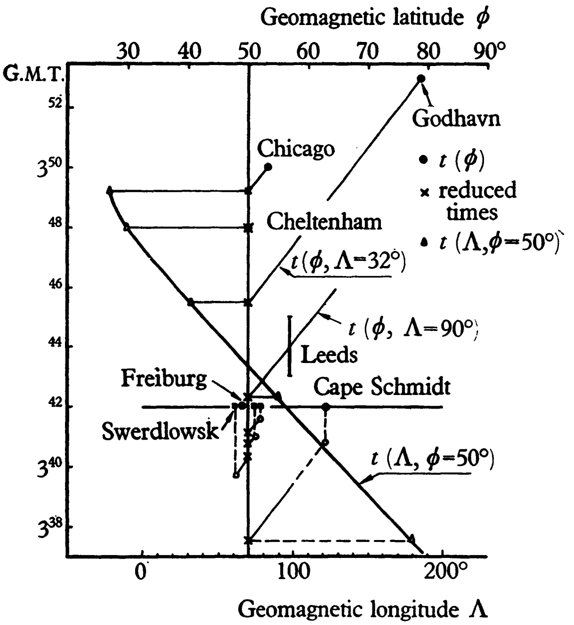

Fig. 8. The time of very first impact as a function of geomagnetic latitude Φ and the dependence of the reduced time on longitude.

coefficient they do not fit such a line. The longitudes of the stations are plotted as triangles against the times reduced for 50° latitude. The coefficient $K_{\tau,\Lambda}$ varies from 20°/min (near Freiburg) to 15°/min (near Cheltenham).

This system is scarcely to be explained by any reflexions of the solar particles. But it is well explained if we assume, that this retarding according to Eq. (14) is connected with the progressing of the first branch in Fig. 6 by interference of the impact zones through the geomagnetic field.

Using Firors representation [14] of Störmer's theory of the orbits we find from his Fig. 4 for 10 GeV/nucleon that a movement of the source by 7° to the north is followed by a movement of the impact zone by 14–30° to the west. The stations fitting the system in Fig. 8 are lying between 100 and 220° western geomagnetic longitude from the sun, C. Schmidt 10° to the west of the sun. This is a confirmation of our analysis in Fig. 8 and its connexion with Fig. 6.

A further help to find out the best fitting value of the direction of **H** is the beginning of the increase in Japan at 3.45 G.M.T. which is only possible by particles with energies > 10 GeV/nucleon and coming to the earth from a source direction with less than 20° northern geomagnetic latitude and a longitude greater than 30° in the east of Japan (Firor's Figs. 3 and 4 [14]). So the best fitting is found with the direction of **H** at this moment 15° to the west and 35° to the north of the sun with $\phi = 40°$. Godhavn is then lying near the upper corner of the bows in Fig. 6 whilst the Russian station C. Schmidt (63° N. and 180°) is in the first impact zone at 3.42 G.M.T.

The direction of **H** may be fixed by this procedure with an accuracy of 30°. The magnetic lines of force come to the earth from the constellation of 'Leo' and thus agree within the accuracy with the direction of the galactic spiral arm we are living in.

Such a magnetic field was assumed by Chandrasekhar and Fermi [15] to explain Hiltner's [16] observations of the polarization of the light from distant stars. They estimated the field strength from the dispersion of the polarization planes to $H = 7{\cdot}2 \times 10^{-6}$ gauss and with quite another method, based on the requirement of equilibrium of the spiral arm with respect to lateral expansion and contraction to $H = 6 \times 10^{-6}$ gauss. The positive or negative direction cannot be distinguished from polarization measurements.

We find the field strength by regarding that, according to our model, the first impact in Japan must be done by particles of the order of 10^{10} eV/nucleon, and that according to Fig. 5 for this time $\epsilon = 0{\cdot}3$. From this we find from Eq. (6)

$$p_1 c \geqslant 3{\cdot}3 \times 10^{10}\,\text{eV} \quad \text{and} \quad H = \frac{3{\cdot}3 \times 10^{10}}{300 \times 1{\cdot}5 \times 10^{13}} = 7{\cdot}3 \times 10^{-6}\,\text{gauss}, \qquad (15)$$

in close agreement with the values by Chandrasekhar and Fermi [15]. The given model explains the retarding effects of the first beginning at all stations. The special curve for Godhavn in Fig. 2 results from the rotating of Godhavn by 3 hr into the best position (as the North American stations do within an hour) and the slow accumulation of the higher energies in this zone according to the branches in Fig. 6. The high spread of the apparent source over a high region of latitude ensures for a long time the staying of all stations in impact zones. Only Mount Norikura leaves it earlier, but at that time the radiation impact in Japan was over.

Furthermore the model explains the high latitude effect of the solar radiation in the end-phase and the narrow energy spectrum, that Pfotzer [17] derived from this latitude effect assuming isotropic radiation outside the earth's field. Fig. 5 demonstrates the suppression of high energies for higher τ in proportion to E^{-2} by the selection in the field.

The hyperbolic decreasing law for the intensities at all stations is another simple consequence of the postulated field.

Particles of homogeneous velocity ($\beta_1 c$) coming from a narrow source with undeflected propagation reach a surface normal to the direction of propagation at the time t after ejection with a density in proportion to t^{-2}. Particles moving in the direction of a magnetic field are (in large scale) held together. The intensity is in proportion to t°. Particles moving nearly normal to a magnetic field spread only in the direction of the field and not in the direction normal to velocity and field. They arrive after a time t with a density in proportion to t^{-1}. Such particles we have to consider at higher τ, as $\cos\alpha$ then gets very small.

At every time t particles arrive along a path the length of which corresponds to only this time and their front density is

$$N(t) = N_1/t \text{ particles cm}^{-2}.$$

Our curves in Figs. 1, 2 and 3 give the number of particles per second

$$n(t) = \frac{dN(t)}{dt} = \frac{N_1}{2t^2}, \tag{16}$$

whatever the special orbits are.

This law can only be understood, if there is a short time of ejection compared with t itself, if the angular space from which particles fall into the apparatus is constant and if the particle energy is constant. These conditions are fulfilled by our model itself from the moment when the impact reaches the full aperture of the apparatus. And this is depending on the geomagnetic situation.

In Fig. 9 the ratio $\quad V = N_{\text{measured}}/(N_1/t^2)$

between the measured intensity at time t and the final intensity extrapolated backwards is drawn for some cases given in Figs. 2 and 3. The first beginning of impact is a point on these curves, as far as it is known. The curve for the neutron measurements in Ottawa indicates two components.

Fig. 10 shows on a map in geometrical co-ordinates (and Mercator's projection) the transformed Fig. 6 for the situations on 23 February 1956, 3.42, 19 November 1949, 11.00, 25 July 1956, 16.00 and 28 February 1942, 11.10. These situations are suitable to explain the quite different behaviour of solar cosmic radiation at these occasions, which are also best

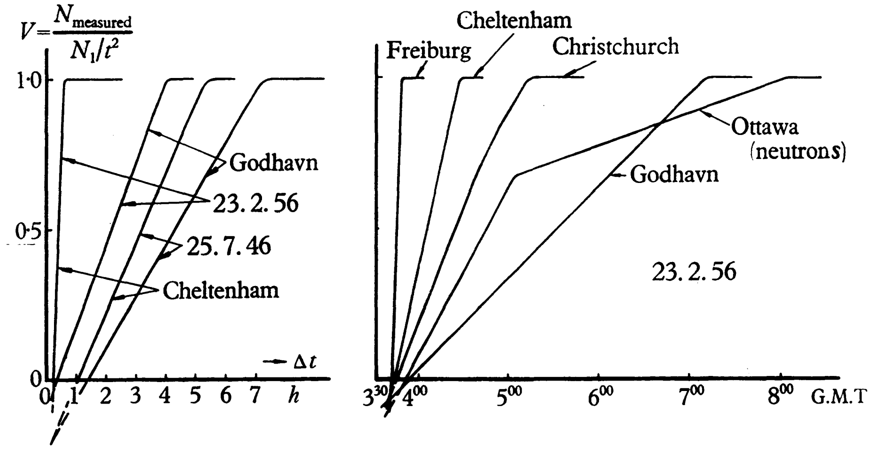

Fig. 9. The ratio between the measured increase, N_{measured}, and the increase extrapolated backwards from the decreasing law of the end-phase. The ratio is plotted as a function of time.

seen in Figs. 3 and 9. Especially, the much longer times between the beginning of the flare and the radiation impact on the earth at these occasions proves to be a consequence of the model, caused by the other value and orientation of ϕ. Five hours after the flare Cheltenham was lying in the main impact zone for the branch drawn in Fig. 10 for 16.00 G.M.T., just at the left-hand side, whilst Europe was leaving it. That is in good agreement with observation. For a field in the direction from the sun, America had been in the first impact zone of the eastern branch one hour after the flare. For the galactic field this eastern branch does not exist.

This is a confirmation of the galactic origin of the acting field. Only for 19 November 1949 the impact in Godhavn is no question for a field from the direction of the sun, whilst for the assumed interstellar field there is a difference of the order of 30°.

The decreasing law itself might also be explained by solar fields of the type discussed by Alfvén [18]. They might correspond to our case with $\phi = 0$. In this case, in a figure corresponding to our Fig. 6 the lines, at every time, are full circles round the centre $H \equiv S$; the angular radius being given by $\cos \alpha = 1/\tau$. This model gives a high gain in arriving particles, but it does not explain the long running times of the particles for 25 July 1956. The running of the first impact to the north is somewhat faster than in the case of Fig. 6 but stops before reaching Godhavn. This is because the direction of the sun is now in the centre from which α is to be measured.

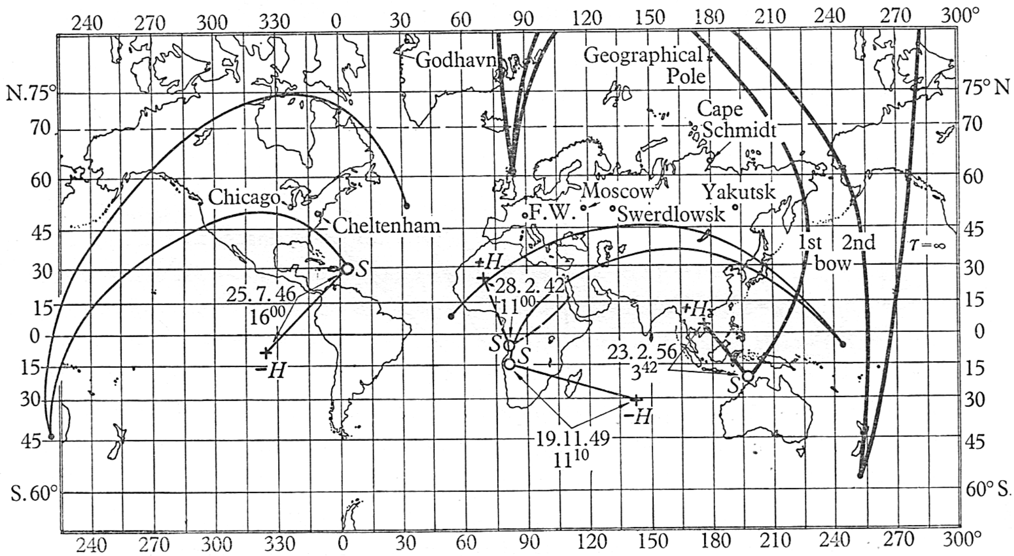

Fig. 10. A transformation of Fig. 6 on a map in geophysical co-ordinates and Mercator's projection. The apparent source outside the geomagnetic field moves along the zenith of the heavy lines. The field estimated from the intensities on 23 February 1956 is assumed to be the same on the other dates. H denotes the direction of the field, S that to the sun at the beginning of the flares. For higher τ-values the lines move according to the earth's rotation.

In this case the running velocity of the first impact towards western longitudes is also slightly greater, but the difference is too small to give a discrimination. But in Japan the first impact ought to be at $\tau = 2{\cdot}0$, i.e. at least 8 min after the first impact in Europe and this rules out this direction of the field.

3. CONCLUSIONS

From the given comparisons of theory and observations we conclude that the interstellar field exists. A severe consequence of this field is that the earth can never be reached by solar particles of energies less than

7×10^9 eV/nucleon (see note added in proof). This value holds for the best positions in spring and autumn. In summer and winter double the energy is needed. But at these times flares on the other side of the sun might also be effective on the earth. The midnight effects which we formerly found [19] fit in this image.

This field is able to make cosmic radiation fully isotropic to very high energies if it exists with a nearly unique direction along the whole width of our spiral arm. The question now arises how do the solar plasma clouds move in this field? Apparently they are not deflected and we think that the very low-energy electrons in these clouds prevent the interstellar field from entering the cloud of a neutral plasma. For this a current sheet must be set up around the border of the cloud in the direction normal to the field. As the field is constant at every place passed by the cloud, there results no further deviation of the velocity vector of the cloud.

For further investigations on this field the dense network of stations and an exact determination of the times of beginning increase is of greatest importance.

The author thanks the *Deutsche Forschungsgemeinschaft* for financial help.

Note added in proof

When this paper was finished for the Stockholm Conference we had no knowledge of the papers of Meyer, Parker and Simpson [20] and of Winckler [21] that give evidence of the impact of low energy primary particles with energies between 1 and 1·5 GeV from balloon measurements in the afternoon [20] and in the evening [21] of 23 February 1956. This is in contradiction to our statement, that energies below 7·5 GeV could not reach the earth from the sun through a magnetic field as evaluated in our paper.

The high-latitude effect between Berkeley and Ottawa or Stockholm indicates furthermore the impact of particles with smaller energy though this might also be understood from the selection of other orbits in higher latitudes. It is essential that the primaries do not arrive in isotropical distribution in our model. This anisotropy was distinctly revealed by measurements with inclined counter-telescopes by Sandström [22] and by Trefall and Trumpy [23]. In connexion with this problem reference should also be given to a recent investigation by Brunberg [24].

Low-energy particles from the sun are possible in our model if ϕ gets small, this implies that the lines of magnetic force are parallel to the line connecting the sun and the earth. We discussed some objections against this case. If an interstellar field has this direction at the end of February and maintains this direction respective to fixed stars, the special curves in Fig. 3

might be understood. The field strength of such a field with $\phi = 0$ comes out to have nearly double the field strength of that discussed in the paper with $\phi = 30^\circ$. Another possibility, we must account for, is that the low-energy particles measured in the stratosphere do not come from the sun but are generated nearer to the earth.

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Discussion

Eckhartt: As far as I understand the time 3^{42} seems to have a particular meaning in your theory. No onset should be measured before this time at any of the stations. How is this reconcilable with the fact that Hobart measured an earlier onset, 3^{39} as far as I can remember?

Ehmert: The time 3^{42} corresponding to $\tau \approx 1.20$ allows a first impact at $3^{40.3}$ for undeflected particles. Dr Fenton indicates the onset time at Hobart at $3^{41 \pm 2}$ G.M.T.

van de Hulst: Were you able to infer the direction of the magnetic field in the spiral arm from the observations by means of your calculations?

* My thanks are due for a kind communication in exchange of data before publication.

Ehmert: The direction of the field is obtained from fitting the times of the first increase of solar cosmic rays in Japan and in Godhavn. It was not implied.

Alfvén: Would not a solar flare occurring three months before or after an onset exhibit quite different properties?

Ehmert: Yes, if the field is not perpendicular to the ecliptic. With the evaluated direction the particles had to run, at 25 July in 1946, in a direction nearly perpendicular to the field.

Alfvén: Would not the interplanetary magnetic field give about the same result?

Ehmert: Yes, but the difference taken in the direction north–south is not quite the same in our case. The result depends upon the magnetic field direction.

Gold: I like this basic idea very much. But I also think that the spiral arm magnetic field can hardly be expected to preserve its direction in the solar system with the sweeping action of the solar activity which we know to move the intervening gas and hence the field. But that hardly detracts from the attractive theory; it only makes this agreement of direction a little fortuitous.

Ehmert: Yes. It is quite astonishing that a systematic effect due to a rather well-defined magnetic field could last for several days; actually the measurements seem to indicate this.

Gold: Further, impact zones appear to have been absent after about one hour, and one would like to know whether adequate 'washing out' results from the arrival of particles not with isotropy, but from a plane containing the earth. This would be the situation in the presence of a homogenous field and for late particles.

Ehmert: A look on Firor's results giving the connexion between the geomagnetic latitude of the source and the western longitude of the station shows that in the final state there are sufficient impact possibilities. Humps in the intensity-time curves may be possible.