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# ON THE PROBLEMS OF THE ORIGIN OF GEOMAGNETIC STORMS

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## Contents

# INTRODUCTION

The study of questions concerning the origin of geomagnetic storms represents a very topical problem of a wide scientific and practical range; for this reason relatively great attention is at present devoted to it. The aim of the present paper, apart from some new conclusions, is to give a comprehensive interpretation of the results obtained by us when studying the connection between geomagnetic and solar activity and to contribute towards an evaluation of the knowledge obtained hitherto in this field of research. In investigating the relations between the two effects the paper starts out with a brief discussion of solar events and the mechanism of geomagnetic storms, which is included in order to clarify the dependences given. The paper tries to point out the complexity of the problems solved.

Geomagnetic storms, which according to the character of their expression can be divided into several groups, are caused essentially by processes taking place on the Sun. A neutral cloud of ions and electrons of solar origin approaches the region of the Earth, where it is influenced by the latter's magnetic field. At such a mutual effect of the dynamic and magnetic factors an electrical current system is induced in the cloud. This leads to the compression of the Earth's magnetic field and thus to the origin of the first phase of a geomagnetic storm. As is seen, a relatively complicated mechanism marks the actual process of the formation of a storm. This mechanism can be divided into several partial stages as a function of the place and the conditions in which these processes take place.

The basic source of all geomagnetic disturbances of the external field are processes taking place on the solar surface and in the corona. It is well known that the active regions on the Sun exhibit relatively strong magnetic fields which influence the movements of glowing solar matter on the surface and in the neighbourhood of the Sun. The forms of such flow and the movement of matter differ and also the expressions of such events, as observed on the solar disc, have a quite definitely defined character. An important object of present-day research is to clarify which of these processes may be geoactive.

It is thus important to study the composition of solar corpuscular streams, and particularly to determine whether they can maintain and carry with them part of the magnetic field from the Sun. The study of this question may contribute towards explaining the fact that some magnetic storms are not followed by a storm of cosmic radiation.

Another open question is how corpuscular streams behave in the space between the Sun and the Earth before they reach the region of the geomagnetic field and to what extent they are braked by the interplanetary gas.

Another field of research deals with the space in the neighbourhood of the Earth, where complex processes take place due to the motion of particles in the magnetic field. The hydromagnetic processes obviously taking place here are certainly strongly dependent on the conditions and physical composition of the outer atmosphere. The questions of the laws of interaction between magnetic fields and fluid-motion are also very important despite the fact that many new results have been obtained by observations using satellites.

The basic material for studying geomagnetic storms are their expressions as recorded at magnetic observatories. If, however, we wish to explain their physical causes and the influences to which they are subject during their formation and to contribute towards explaining the mechanism of their formation and their prognoses, the results of studying processes taking place on the Sun, which are the primary cause of geomagnetic storms, must be taken into consideration.

The above-mentioned partial problems show the whole sequence of data from the initial impulse on the Sun up to the expression of the geomagnetic storm on the Earth's surface.

The present paper also aims at contributing, at least along basic lines, towards explaining some of the above questions, particularly as regards processes taking place at the formation of geoactive processes on the Sun and as regards the classification of magnetic storms and the relations between solar and geomagnetic phenomena.

Questions of the magnetic fields on the Sun and the hydrodynamic processes taking place there are discussed. An evaluation is made of the different events on the Sun with regard to whether they may be considered as sources of disturbances in the geomagnetic field. Chapter II contains some brief notes on the conditions in interplanetary space.

It is well known that a whole series of geomagnetic disturbances occur which differ from one another. This question of the classification of storms is dealt with in Chap. III.

Chapter IV gives some data on processes taking place at the interaction of corpuscular streams with the geomagnetic field.

In Chap. V the authors sum up their results of studying the dependence of magnetic storms on solar activity. An evaluation is also made of the results obtained up to now from which some interesting conclusions are drawn as to the causes of magnetic disturbances.

The conclusion contains an evaluation of present-day knowledge as well as describing the main tasks to be solved in the immediate future.

## I. EVENTS ON SUN

The processes, which take place on the solar surface and which are connected with the interaction of the motion of glowing matter and the magnetic fields are very complicated and heterogeneous. However, one can find among them a series of processes exhibiting a certain system in their occurrence and form. It is found that magnetic fields on the Sun have a great influence on the production of different solar formations. Although it cannot yet be deduced whether parts of the magnetic fields are transferred from the Sun to the Earth with the corpuscular stream and whether they influence the magnetic field of the Earth directly, in any case these fields play a role in the ejection of particles from the solar region. The importance of studying them is therefore obvious.

Analogously as for the Earth, there exists a total magnetic field of the Sun which can be modelled by means of dipoles. Although the intensity found for the total field reaches relatively small values compared with the magnetic fields accompanying some other solar effects, its dimensions show its decisive influence on the formation of a corona of so-called minimum type. If regions of strong local fields occur then they greatly disturb the total field in the neighbourhood of the Sun, which, due to their high intensity, loses its dipolar character.

From the geoactive point of view the formations occurring in connection with sunspots as well as the spots themselves are important; the effects are included under the concept of a centre of activity. The development of such a centre is governed by certain laws while the lifetime of the phenomena which occur is not the same. The whole cycle of development of such a region has been described in detail in [1].

We are interested in those formations about which it can be assumed that they might be the causes of geomagnetic storms. Opinions held hitherto on this question have varied a lot and have been far from giving a clear answer. They can be divided into three groups:

a) The causes of geomagnetic storms have been ascribed to the occurrence of spots on the Sun. Earlier statistical comparisons, which paid no attention to other processes occurring in the spot regions, showed a certain connection particularly for average values from annual intervals; however, the degree of correlation between the two effects decreases with decreasing length of the intervals. At shorter intervals the connection between the two effects can no longer be proved [2]. A more detailed analysis of the solar situation during the occurrence of spots showed that certain connections are apparent between geomagnetic activity and spots of large dimensions. They depend to a great extent also on the mutual arrangement of the spots. The correlation improves [3] if spots with a high flare activity are used in the analysis.

b) For this reason relatively great attention was paid to the occurrence of flares. Certain relations have been found between the occurrence of geomagnetic storms and strong flares. At present flares are regarded in the world as the source of geomagnetically effective corpuscular streams. However, as regards medium and weak flares, no laws were found. For this reason increased attention is paid in this paper to the question of the geoactivity of flares.

c) It has also been shown [4] that the occurrence of filaments in the neighbourhood of the central meridian (CM) results, in approximately 3 to 5 days, in a magnetic disturbance. One might deduce from this that filaments are the source of corpuscular radiation. Coronal rays above filaments were regarded as an even more likely cause of storms [5]. A profounder set of laws was found on the basis of a detailed investigation into filaments and their relation to the coronal formations [6, 7]. The question from the Sun to the Earth with the corpuscular stream and whether they influence the magnetic field of the Earth directly, in any case these fields play a role in the ejection of particles from the solar region. The importance of studying them is therefore obvious.

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Let us now deal in greater detail with the most important solar phenomena from the point of view of the processes which take place during them and with the possible mechanism of their origin.

## 1) Sunspots

It is well known that sunspots have a very strong field, attaining an intensity up to 4500 Oe, compared with the total field of the Sun. It can therefore be assumed that this property plays a considerable role in the equilibrium of sunspots. The mechanical forces appearing during such phenomena are balanced by magnetic pressures. The magnetic flux passing through the sunspot region can be expressed by the relation [8]

$$\Phi = \int H \, d\sigma \qquad (1)$$

where $\sigma$ is the surface element, $H$ the magnetic field. It is seen that a change in flux takes place in approximately the same way as the formation of a sunspot region. We can therefore assume [9] that the field already existed in the deeper parts below the surface of the Sun before the spot became visible and that it is brought to the surface by the action of some mechanism. This is confirmed by the relatively long-term existence of solar centres of activity while the sunspots characterizing the time maximum of the field have a much shorter life. In the interior of the Sun, on the assumption of strong convection, torsional oscillations may be produced. As a consequence of the uneven rotation of the Sun certain parts of the mass may be exposed to oscillations in longitude and latitude; they begin to get near to the surface of the Sun and cause considerable distortion of the lines of force (Fig. 1). The pre-condition for this process is a relatively high degree of magnetic rigidity. For a non-uniformly rotating Sun, having a magnetic field, one may consider that it has lines of force frozen into its matter. Its field can be constant on the assumption that it is symmetrical around the axis of rotation.

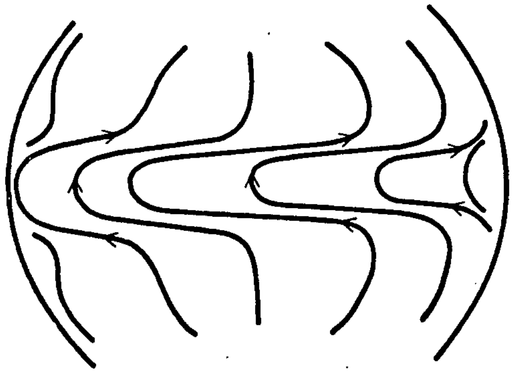

Fig. 1. Distortion of magnetic lines of force near to solar surface at approach of torsion wave to equator.

According to the law of isorotation [10] it holds that

$$\partial \boldsymbol{H}/\partial t = (\boldsymbol{H} \,.\, \mathrm{grad})\, \boldsymbol{v} - (\boldsymbol{v} \,.\, \mathrm{grad})\, \boldsymbol{H} \tag{2}$$

where $\boldsymbol{H}$ is the magnetic field, $\boldsymbol{v}$ the velocity of motion of the mass.

In cylindrical coordinates $R$, $\Phi$, $z$, where $R$ is the distance from the axis of rotation, $\Phi$ the corresponding angle and $z$ the distance from the equatorial plane, the above equation can be resolved into components. Let $\omega$ be the angular velocity so that $\boldsymbol{v} = R\omega$. If the stationary state of rotation is disturbed as a result of the azimuthal removal of part of a body, the disturbance is equivalent to a torsional magnetohydrodynamic wave propagated along the lines of force. Let the motion be defined by the component of the undisturbed angular velocity $\omega_0$ and the component $\omega'$ as a result of the disturbance. Analogously, let the field $\boldsymbol{H}$ be composed of the undisturbed component $\boldsymbol{H}_0$ and the disturbance field $\boldsymbol{h}$. Then we obtain

$$\partial h_\Phi/\partial t = R(\boldsymbol{H}_0 \,.\, \mathrm{grad})\, \omega' \,. \tag{3}$$

In the component $\Phi$ of the equation of motion there then appears only the electromagnetic force $\mu[\boldsymbol{j} \times \boldsymbol{H}]$ so that this component reduces to

$$4\pi\varrho R^2(\partial\omega'/\partial t) = \mu(\boldsymbol{H}_0 \cdot \mathrm{grad})\, Rh_\Phi \,. \tag{4}$$

The permeability $\mu$, about which it is assumed that it is equal to one, is usually left in the expressions to facilitate transformation. Expressions (3) and (4) form important relations in the theory of magnetohydrodynamic waves. They can be used on the assumption that the disturbance field $\boldsymbol{h}$ is much larger than the field $\boldsymbol{H}_0$ and thus the torsional oscillations may form a large azimuthal field $\boldsymbol{h}$ from the small field $\boldsymbol{H}_0$ in the meridional planes [9]. Strong convection may then cause a decrease in angular velocity in the interior of the Sun. This fact then causes the torsional magnetohydrodynamic wave to propagate along the lines of force in the direction of the surface (Fig. 1). It may be considered that this torsional wave proceeds against the equator. If it gets close to the surface the lines of force there form a band around the Sun. On penetration to the surface two regions with reversed magnetic polarity may then be formed; in one the lines of force intersect the surface in the outwards direction and in the other they return inwards. These regions can then be regarded as a pair of sunspots with reverse magnetic polarity.

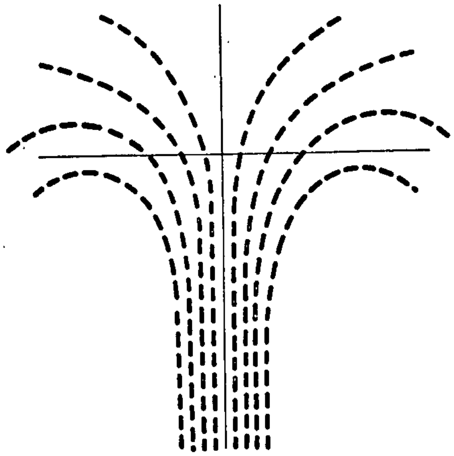

Fig. 2. Hypothetical distribution of magnetic lines of force at their exit from spots on surface of Sun (vertical cross-section of spot).

Due to the high values of the magnetic field in the spots the magnetic pressure $(\mu H^2/8\pi)$ here reaches relatively high values of the order of $1.6 \times 10^5$ dyne/cm². This magnitude causes the mass in the regions around the spots to be pressed back and the lines of force lose their original vertical direction. They are detained in the sub-surface layers and above the surface, as is seen from Fig. 2.

Due to the relatively strong magnetic fields in the spots and in their immediate neighbourhood solar matter can hardly be released outside the region of the Sun; the movements of the mass here are governed by their magnetohydrodynamic laws. Spots can therefore hardly be regarded as a direct source of geomagnetic disturbances.

## 2) Flares

Flares appearing as short-term sudden effects in the neighbourhood of sunspots are fundamentally characterized by a strong light increase in part of the floccular field and not by the ejection of matter. In a period of strong solar activity flares occur very frequently, of the order of once in two hours. They do not usually appear at distances larger than 100 000 km from a group of spots but always inside a facular region. It is often observed that in a period of flare occurrence existing filaments change or even disappear, new filaments and surges are formed even at large distances from the flare. Sometimes, of course, the filaments closely neighbouring a flare remain without change. It was found [11, 12] that solar flares appear in the region of zero line of the magnetic field dividing off the places with opposite magnetic polarity.

Although the temperature of the spots is relatively low much higher temperatures are found in their neighbourhood during flares. These are very probably electromagnetic in origin. During the motion of solar mass in the magnetic field of a spot it can be assumed that the electrical fields produced here may be the cause of electrical currents and the latter are then the source of tremendous temperature effects. Their sudden origin in the form of a light increase may then be apparent as a solar flare.

Large flares are usually conjugate with spots having irregular polarity; in this case they usually have a complicated shape.

During theoretical considerations an investigation was made into the question of the formation of a corresponding discharge in ionized gas considered as the probable physical mechanism of the flare and the connection between flares and the surrounding formations was studied.

During motion in an electric field the electrons collide with the ions [13]. At such collisions the fast electrons lose relatively little energy. On the other hand, during their motion they obtain energy from the electric field present. But with increasing temperature the number of collisions decreases which leads to a further increase in the energy of the electrons. For a strong electric field this increase may continue without limitation and there thus occurs an effect analogous to an electric discharge.

Let the mean velocity **v**, the electric field **E** of which acts on an electron, be given by

$$\mathbf{v} = - e\mathbf{E} \,.\, \mathbf{V}, \tag{5}$$

where $\mathbf{V}$ is the velocity of the electrons passing through the solar mass. Then the change in energy of the electrons

$$dW_e/dt = -e\mathbf{E}\mathbf{V} - 2m_e\nu(W_e - W_i)/m_i. \tag{6}$$

The second term on the right-hand side represents the energy loss of the electrons on collision with the ions, where $\nu$ is the frequency of collision, $m_e$ and $m_i$ the masses of the electrons and ions. On certain assumptions, when the electric field is perpendicular to the magnetic field present, we obtain

$$\frac{dW_e}{dt} = \frac{2m_e\nu}{m_i}\left(W_i - W_e + \frac{m_i e^2 E^2 W_e^3}{2m_e^2 a n_i + W_e}\right), \tag{7}$$

where $a$ is a value defining the magnetic field present and $n_i$ gives the number of collisions. The expression in brackets is negative for large values of $W_e$, which may lead to an unlimited escape of electron energies. It thus follows that the discharge takes place along the lines of force; this is also obvious from the fact that on motion across the lines of force the mechanical force $\mu[\boldsymbol{j} \times \boldsymbol{H}]$ would rapidly change the motion of the mass.

As regards the place of origin, on the one hand we considered the region of zero fields between the spots and on the other hand we assumed the discharge motion inside the flare to be along the lines of force of the magnetic fields of the spot, the shape of which is very irregular at turbulent motions of solar matter. The complexity of the phenomenon under investigation, however, requires further detailed study.

While flares rise to relatively very low heights above the solar surface, eruptive surges are often produced in their neighbourhood. These appear as bright short-term prominences rising to relatively great heights, up to $10^5$ km.

### 3) Filaments (Prominences)

Filaments appear on the solar surface as relatively stable formations in the shape of long dark ribbons. In some opinions, coronal matter condenses in them along the magnetic lines of force. It can be deduced from this that the stability of the filamentary arch-like shapes is to a great extent influenced by the magnetic fields and the relatively high magnetic rigidity. The density of a filament is approximately 100 times greater than the surrounding corona; the temperature corresponds to $\frac{1}{200}$ [1]. A magnetic field acts not only on prominences but also on the corona while there often exists a close relation between these two formations. A convenient grouping of the fields may then cause a rise in a certain part of or the whole prominence from the Sun while, at the same time, part of the corona may be expected to flow out above the rising prominence [14].

A satisfactory theoretical explanation of the origin of filaments has not yet been given. At present the existence of filaments is relatively well explained in the theory of magnetic arcs [15]. It is assumed that a filament lies along a line of force of a magnetic field. The weight of the filament mass is compensated by the forces due to the distortion of the lines of force, defined by the factor $K$. Then the magnetic pressures can be converted to the forces $K\mu H^2/8\pi$, which must be equivalent to the expression $\varrho g$ (product of density and gravity) if equilibrium is to be ensured. For this it is necessary that for the corresponding values of $\varrho g$ and $K$ there be present a field $H$ of an order of at least 50 Oe. Such a value $H$ can be quite easily assumed in the neighbourhood of spots; the long-term duration of the existence of prominences can then be explained by magnetic rigidity. The mass of a filament sometimes appears as though it were wedged into a shallow depression in the beam of surrounding lines of force. Such a favourable grouping of the magnetic field contributes towards the filament remaining suspended above the solar surface for a long time. A solution of the magnetohydrodynamic equation

$$0 = -\operatorname{grad} p + \varrho g + \mu[\boldsymbol{j} \times \boldsymbol{H}] \tag{8}$$

has already been found as applied to this case, where $p$ is the pressure, $\varrho$ the density of the medium and the term $\mu[\boldsymbol{j} \times \boldsymbol{H}]$ expresses the force of electromagnetic origin [15]. The equation of the corresponding lines of force in a prominence is given in the form

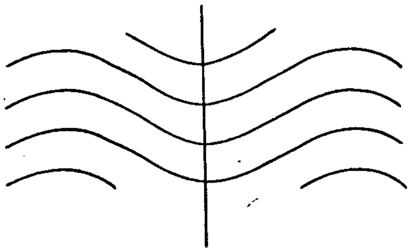

Fig. 3. Course of magnetic lines of force according to Menzel's theory.

$$f = \exp[(z - z_0)/\lambda] \tag{9}$$

where $z$ gives the vertical height, $\lambda$ a certain constant. The shape of the lines of force is seen in Fig. 3.

However, such a theoretical conception expresses the carried prominence only in rough outlines and isolated from all the surrounding influences; the theory of the origin of filaments will therefore have to be elaborated further.

The theory of jet streams [16] is based on the assumption that a filament is the trace of electric currents, analogously as in a discharge tube. It is seen, however, that with such a mechanism the required stability, which is normal for filaments, cannot be ensured. For this reason the preceding theory seems more favourable for the explanation.

## 4) Relations Between Spots, Flares and Filaments

The laws governing the formation of an activity centre and its further development prove that phenomena occurring during the different phases may be related to and influence one another. Although the characteristic features of the different phenomena are quite different, as regards their duration, form, temperature and place of occurrence, some connections have been found although not always proved. The magnetic fields are seen here to have a very strong effect; then, as a function of their grouping, the partial effects may influence one another. Some scientists even assume that the magnetic fields are the direct causes of spots, flares and the corona. As regards the connection between them, it has not yet been decided for certain whether the flares activate the filament or whether the two phenomena are different results of the same cause (change in magnetic field). Here the influences of structure of the magnetic field present and not only the mechanical forces obviously play a role.

During activation the filament may also disappear but often, particularly in regions of strong fields, it reappears in its original form after a short time. In the solar atmosphere there is a connection between the motion of the mass and the magnetic fields and current systems. This is very strong in the region of sunspots which have large magnetic fields. Therefore the corona above the group of spots is also strongly deformed by local magnetic fields. Sudden changes in their grouping may then result in the deformation of the corona.

It follows from the above that all the events in the activity centres are fundamentally influenced by the occurrence of magnetic fields and their relatively strong effect on the corona and coronal formations. Particular attention must therefore be devoted to these questions.

## II. CONDITIONS IN INTERPLANETARY SPACE AND EXOSPHERE

An important factor in the propagation of corpuscular streams after their ejection from the solar region is the space between the Earth and the Sun, the physical properties of which may to a great extent influence the behaviour of a moving cloud of corpuscular particles. Definite conclusions have not been reached in determining the density and temperature of interplanetary mass. It is assumed that the density is approximately $10^3$ particles/cm$^3$.

Different models have been proposed for the interplanetary magnetic field. While earlier the field was regarded as negligible, it has been found that in this space there exist regions with a rapid flow of plasma, obviously moving in different directions [17]. Many scientists assume that the magnetic field is produced here and that it is maintained by the ejection of parts of the magnetic field of the Sun, caught on the corpuscular radiation from the active solar regions. The value of the interplanetary magnetic field is approximately $2.5 \times 10^{-5}$ Oe. Fresh data along these lines are provided by investigations into the paths of cosmic rays which are influenced and guided by this field. It can be assumed that there exists a relatively continuous transition between the geomagnetic and the interplanetary magnetic fields.

A great contribution towards explaining the conditions in interplanetary space and the exosphere has been made by material obtained by means of satellites and cosmic rockets. The discovery of two radiation belts (van Allen) [18] surrounding the Earth, at distances from 700 km to 60 000 km from the Earth, in which the very intense radiation of high-energy particles plays a role, has meant the finding of a further important link in the chain of events beginning with activity on the Sun and ending with a geomagnetic storm. The charged particles are caught by the magnetic field of the Earth. From the equatorial regions they move along the lines of force towards the poles and cause an increase in magnetic intensity. As a result of the vertical component of the geomagnetic field the motion and oscillation of the particles about the lines of force is damped. The inhomogeneous geomagnetic field causes the particles to move in the longitudinal directions on the surface of the level, forming two ring-shaped regions of maximum radiation intensity (Fig. 4).

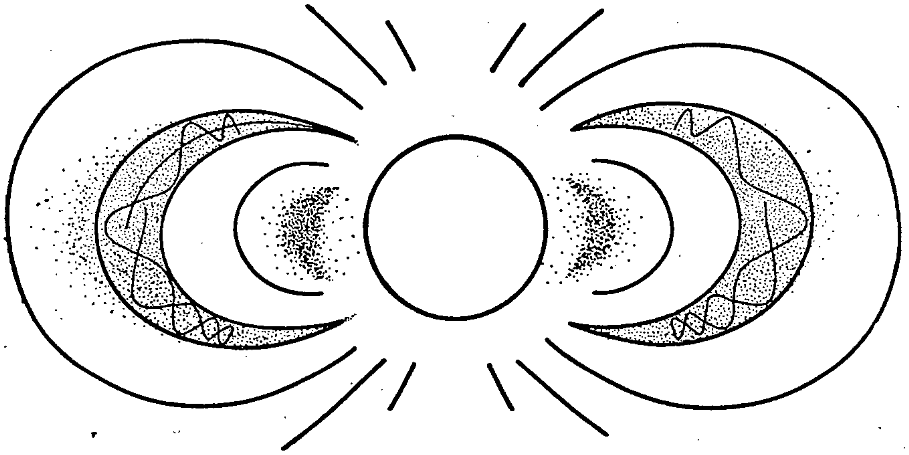

Fig. 4. Distribution of radiation (van Allen) belts.

The composition of the particles is not the same in the two radiation belts. In the outer belt the energy of the electrons fluctuates between 40 keV and 5 MeV, while for protons it reaches a maximum of 200 keV. On the other hand, the energy in the inner belt is quite different; for electrons it reaches a maximum value of 600 keV while for protons it has a much higher value (from 10 to 200 MeV).

The density of the radiation belts is not always the same. Solar geoactivity apparently causes an increase in the concentration of particles in the belts; however, calculation shows that the lifetime of protons of the inner belt is limited to a maximum of a few weeks. The outer belt would also disappear in a short time (a few hours) if it were not for the effect of a certain source of particles and the mechanism working inside the magnetic field which keeps the particles in its domain although they no longer have a high energy.

There are relatively few data available on the character of interplanetary space and the exosphere so that conclusions as to the conditions reigning there are far from being complete. A further study of the phenomena, particularly in radiation belts, could contribute towards explaining the conditions necessary for the motion and behaviour of high-energy particles.

## III. GEOMAGNETIC ACTIVITY

### 1) Time Variations of Geomagnetic Field

It is already quite clear that the basic cause of geomagnetic activity is solar radiation. Since geomagnetic storms are only one, although the most pronounced, form of the set of time variations of the geomagnetic field which must be taken into consideration when investigating their connection with solar phenomena, it will be expedient to make a few brief remarks of a broader aspect on the time variations of the geomagnetic field in general. On the other hand, the solar radiation itself represents a wide sphere of fundamentally different wave and corpuscular components so that one can quite obviously expect different effects and mechanisms of expression, and this is actually the case.

If we disregard the secular variation of the geomagnetic field, which is fundamentally given by the processes taking place under specific conditions deep in the body of the Earth, and is thus outside our sphere of interest, all the other time variations are conditioned directly or indirectly by solar radiation. This conditional state may be understood as "static" if a certain time variation of the geomagnetic field is excited just by the mere existence, more or less permanent and constant, of the appropriate component of solar radiation, or as "dynamic" if the time variation is excited only at sudden and substantial increases in the corresponding components of solar radiation.

A typical example of "static" conditions is the variation of the geomagnetic field on quiet days Sq, and from the sphere of "dynamically" conditioned variations, a geomagnetic storm. These examples concern direct conditions. The purest form of variations from the sphere of indirect conditions is the variation caused by tidal influences of the Moon – lunar variation L.

On the basis of a detailed analysis of the above types of variations we proposed the scheme given in Tab. I where the most important variations and processes in the geomagnetic field are drawn up, taking into consideration the character of solar radiation.

Before analyzing it, however, a few remarks must be made on solar radiation. The geomagnetically effective parts, particularly of the short-wave component of solar radiation (X-rays and ultra-violet region) as well as of the corpuscular component (electrically charged particles with energy up to an order of $10^5$ eV), are already quite well known. It should merely be emphasized that in the corpuscular component a strict distinction should be made between *geomagnetically effective* radiation and other *geoactive* radiation (the solar component of cosmic radiation with particles having an energy of the order of $10^9$ eV). Here there are deviations both at emission from the Sun and during interaction with the geomagnetic field: on the one hand, one cannot deduce from the emission of one kind of radiation the simultaneous emission of another kind, and, on the other hand, the interaction of geomagnetically effective corpuscular radiation with the geomagnetic field can be understood as a hydromagnetic process while the penetration of the solar component of cosmic radiation through the geomagnetic field can be interpreted by Störmer's theory [19] (Fig. 5).

We shall not take into consideration below the time variations and processes in the geomagnetic field which are subject to wave radiations and which in their mechanism and results lie outside our sphere of interest.

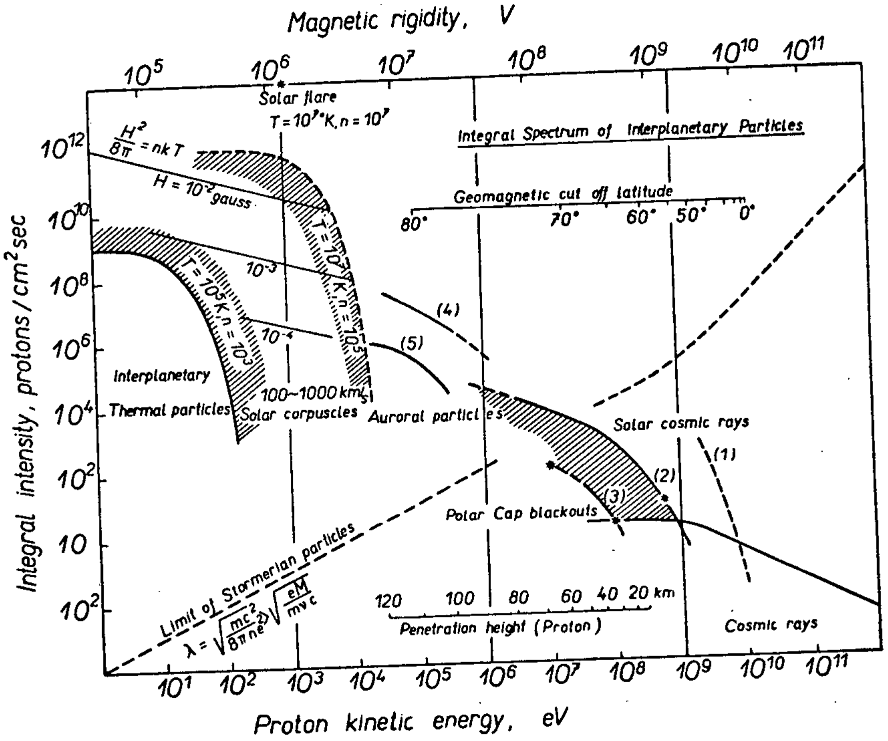

Fig. 5. Survey of basic types and characteristics of corpuscular radiation in space between Sun and Earth (after [19]).

As regards the classification of the time variations of the geomagnetic field subject to corpuscular radiation*) in Tab. I, mention should be made of the following:

*Geomagnetic storms:* The classification is quite obvious. These very pronounced disturbances, some of the characteristics of which will be dealt with in greater detail presently (Chap. IV), are, however, practically always accompanied by the following variations:

*Sudden impulses:* These appear as small changes in the geomagnetic field. Their classification is clear as long as the impulses can be interpreted (after [20]) as a certain "more moderate" analogy to sudden commencements of geomagnetic storms ssc. This is probably the interaction between the more pronounced density inhomogeneities in a constant inflow of charged particles from the Sun ("solar wind") and the Earth's

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*) In the following text corpuscular radiation always means geomagnetically effective solar corpuscular radiation.

Table I

*Plot of dependence of basic variations and events in geomagnetic field on solar radiation (inside square corresponds to corpuscular component of geomagnetically effective solar radiation)*

| Condition | "Statical" | "Dynamical" |
|---|---|---|
| direct | variations Sq<br>sudden impulses | solar flare effects<br>sc and g storms, bays |
| indirect | pulsations *pc*<br>variations L | bays, pulsations *pt* |

magnetosphere. From the point of view of solar events this interpretation can be accepted since a number of processes in the solar chromosphere and corona can be mentioned which might excite the inhomogeneities; these are particularly changes in the floccular fields, small flares, surges and changes in the structure of filaments.

*Pulsations:* In this field of small changes with periods of the order of 1 – 100 sec one can consider two classifications. Apart from the well-known conceptions that the cause of pulsations are hydromagnetic oscillations of the plasmatic medium of the Earth's magnetosphere, excited by the interaction of the solar wind with the surface of the magnetosphere [21], we can also take into consideration the conception that in some cases the occurrence of pulsations is facilitated by the increase in conductivity of the ionosphere at a bay disturbance [22]. As regards solar causes, for the excitation of oscillations one must probably again assume density inhomogeneities in the solar wind and thus also similar causes as in the case of sudden impulses. We have, however, preliminarily pointed out some specific features, apparent in the fact that day-type pulsations *pc* [23] exhibited a tendency to more frequent occurrence after the passage of active solar regions with flare activity through the central solar meridian while pulsations of the night type *pt* showed a tendency to greater occurrence after the passage of regions with probably "quieter" emission of corpuscular radiation [24].

*Bays:* With these disturbances of a regional character we are also forced to make a double classification. The direct condition is obvious, particularly for those bays which actually form some geomagnetic storms and disturbances with a gradual commencement (g-storms) and it also follows from the possibility of the prognoses of such bays on the basis of the character of the solar situation (see Chap. V). Other bays, particularly those which substantially participate in the daily variation of geomagnetic activity with maximum in the evening hours local time [25], lead rather to the conception that in periods of increased inflow of corpuscular radiation, the surplus of particles caught in the Earth's magnetosphere penetrate to the region of polar zones [26].

## 2) Classification of Geomagnetic Storms

When classifying geomagnetic storms, necessary inter alia for a more detailed research of their dependence on solar activity, one can use the quantitative and morphological features of the storms. A quantitative classification makes use of both the course of the geomagnetic storm found directly and that expressed by means of a suitable index of geomagnetic activity.

In the first case the scheme in Tab. IIa is commonly used. The classification is in relation to the energy of the geomagnetic storm, the boundaries are obviously purely conventional and here the well-known dependence of the geomagnetic activity on the geomagnetic latitude is clear. In the second case the *K*-index is used. The scheme, whose boundaries are also conventional, is given in Tab. IIb.

Table II

*Quantitative classification of geomagnetic storms*

| a | | b | | |
|---|---|---|---|---|
| $\Delta H (\gamma)$ | Storm | Max. $K$ | Storm | |
| <150 | small | 5 | m | moderate |
| 150–300 | medium | 6–7 | ms | medium severe |
| >300 | large | 8–9 | s | severe |

$\Delta H (\gamma)$ maximum amplitude of horizontal component of geomagnetic field during storm,
max. $K$ maximum three-hour index $K$ during storm.

From the point of view of solar influences it should be emphasized in connection with the above classification that here there is no simple dependence of the severity of storms on the importance of visible expressions of solar activity, which come into

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From the point of view of solar influences it should be emphasized in connection with the above classification that here there is no simple dependence of the severity of storms on the importance of visible expressions of solar activity, which come into consideration as sources of corpuscular radiation. It is often observed that from the point of view of solar activity insignificant events are followed by important geomagnetic storms and, vice versa, some very important expressions of solar activity remain without a response in the geomagnetic field. (An interpretation of this effect is given in Chap. V.) It seems that much better agreement can be obtained from the quantitative aspect if solar radio outbursts are also taken into consideration [28, 29].

From the morphological aspect geomagnetic storms are commonly classified according to the time sharpness of the onset of a storm and are divided into two types: storms with sudden commencement (sc-storms) and storms with a gradual commencement (g-storms). It can be expected that these two types differ primarily in the magnitude of the density gradient of the particles in the front of the corpuscular stream or even at the side of the stream if the Earth meets a stream which has already lasted for some time. Differences in velocities cannot play such a role here nor do our results show them to be so important as is usually deduced (Chap. V).

From the point of view of solar influences the situation in this method of morphological classification of geomagnetic storms is much clearer than in the preceding case. It follows from the above that sc-storms are preceded by sudden changes in the solar situation connected with the short-term emission of corpuscular radiation or a short-term favourable direction of the emitted corpuscular radiation. On the other hand, g-storms occur after slow changes in the solar situation, accompanied by long-term emissions of corpuscular radiation.

The classification based on the dependence of the character of geomagnetic disturbances on the geomagnetic latitude can also be regarded as a certain type of morphological classification corresponding in a heightened degree to the physical mechanism of the origin of geomagnetic storms as a whole [30]. It is seen that in the belt of low latitudes, up to about 45°, the disturbance takes place synphasically on large regions of the Earth's surface (S-type), in the middle and upper latitudes roughly between 45° to 70° the disturbances may be different even at places only a few hundred km away from one another (L-type), and finally in the polar regions, above 70°, disturbances take place on disturbed days more or less permanently and often occur also on days which are geomagnetically quiet in other belts (P-type).

The dependence of the type structure of a storm on its intensity is important. According to [30] geomagnetic storms with $K_p$ max $7-9$ consist of disturbances of the type S, L and P, have a pronounced storm variation $D_{st}$ and begin suddenly. On the other hand storms with $K_p$ max $3-6$ consist only of L and P type disturbances, no $D_{st}$ variations are seen and they begin with a gradual commencement.

It is possible that the relation between the intensities of S and L type disturbances, together with the possible latitude displacements of the boundary in the 45° latitude, is one of the causes of the occurrence of different types of geomagnetic storms for an otherwise special morphological classification, the results of which will now be mentioned.

## 3) Attempt at New Classification of Sc-storms

The gradual refinement of conceptions as to the connection between solar and geomagnetic activity has made it necessary, and also possible, to solve other special problems. One such problem, also of practical importance for forecasting geomagnetic activity, is the question whether some morphological peculiarities in the course of different geomagnetic storms can be at least partly derived from the morphological peculiarities of solar situations during the emission of the corresponding corpuscular stream. The results would also contribute towards determining to what extent the specific properties of the different corpuscular streams assumed to be given by the different character of the solar situation, where they were emitted, are preserved, i.e. to determining the possible smoothing effect of the medium along the path of the corpuscular stream. The investigations made so far along these lines, the results of which will be given below (details will be published later), represent the first step in a broader attempt at a new classification of geomagnetic storms taking into consideration the character of the solar situation in question.

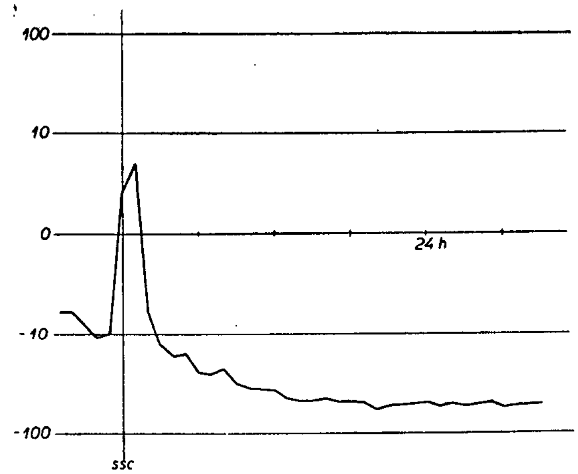
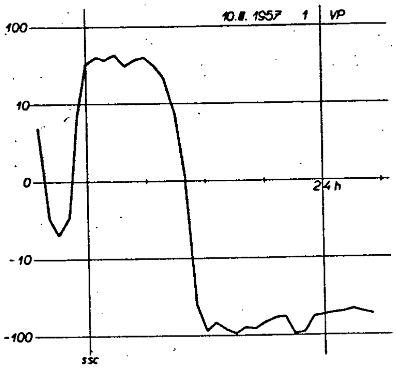


Fig. 6. Average time dependence of horizontal component of geomagnetic field for set of storms used in experiment on new classification of sc-storms. Vertical axis: $H_d - H_q$ ($\gamma$).

The records of 90 geomagnetic sc-storms on standard magnetograms from the geomagnetic observatory in Průhonice ($\lambda = 14°33'$, $\varphi = +49°59'$, $\Lambda = 97.5°$, $\Phi = +50.1°$) were used for the classification. The typical course of a storm, obtained as the average of all the cases by the usual method of the displacement of the epochs of storm commencements (storm variation $D_{st}$), is shown in Fig. 6. After a detailed evaluation of the different courses of geomagnetic storms as regards similarity and deviations from the typical course, the whole set of storms could be reliably divided into a number of special types according to exactly defined simple criteria. Here, for the sake of brevity, we give only the plots of the most pronounced representatives of the different types (Fig. 7) instead of the definitions used in the classification.

Type analysis showed that the majority of geomagnetic storms of the set in question has the expected "two-phase" course, both phases of which can be modified quite differently. It is interesting, however, that apart from this a not insignificant part of the set exhibits a definitely "one-phase" course, also differently modified. The small remainder is formed by some storms of a more complicated character which obviously


10.II. 1957
1
VP
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24 h
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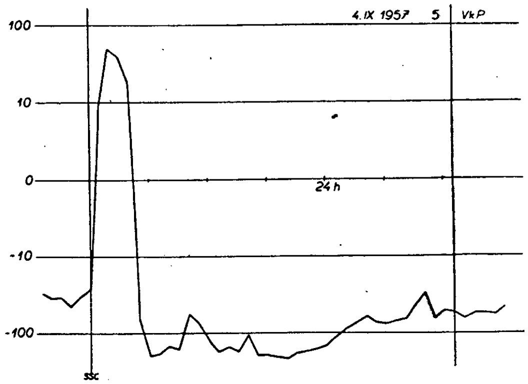
ssc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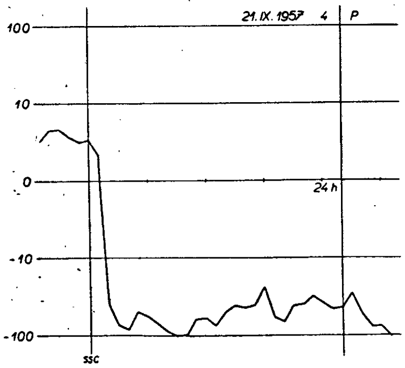
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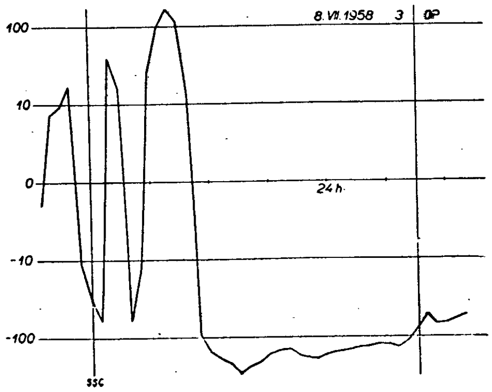
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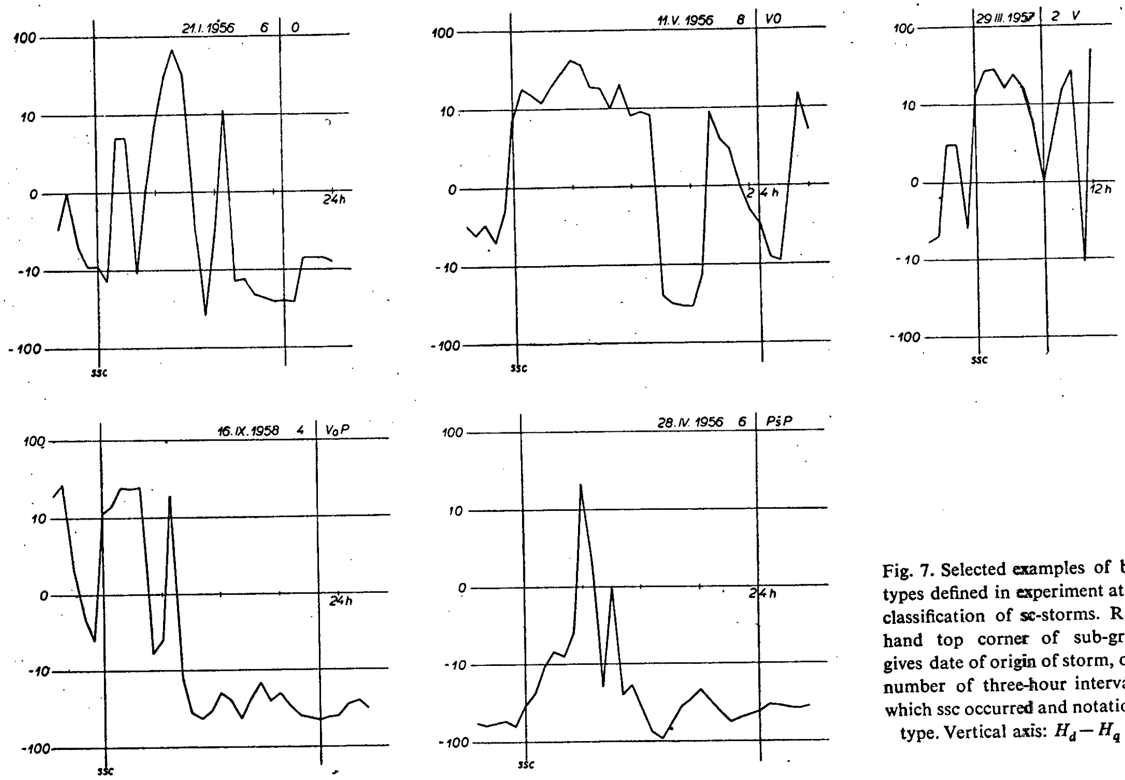

Fig. 7. Selected examples of basic types defined in experiment at new classification of sc-storms. Right-hand top corner of sub-graphs gives date of origin of storm, order number of three-hour interval in which ssc occurred and notation of type. Vertical axis: $H_d - H_q$ (γ).

originated by the overlapping of two or more disturbances, as is also indicated by the length of their duration. The statistics of the occurrence of the different main types is given in Tab. III.

In order to decide whether the deviations of the different storm courses from the typical course cannot be caused inter alia also by the different time of day at which the storm occurred, the material was classified into partial sets according to the three-hour period in which the storm started.

The average storm courses of these partial sets, obtained by displacing the epochs, are on the whole similar (Fig. 8), which indicates that the possible influence of local time is very small. This is also supported, as was to be expected, by the random distribution of the points in Fig. 9, where all the investigated storms are plotted taking into

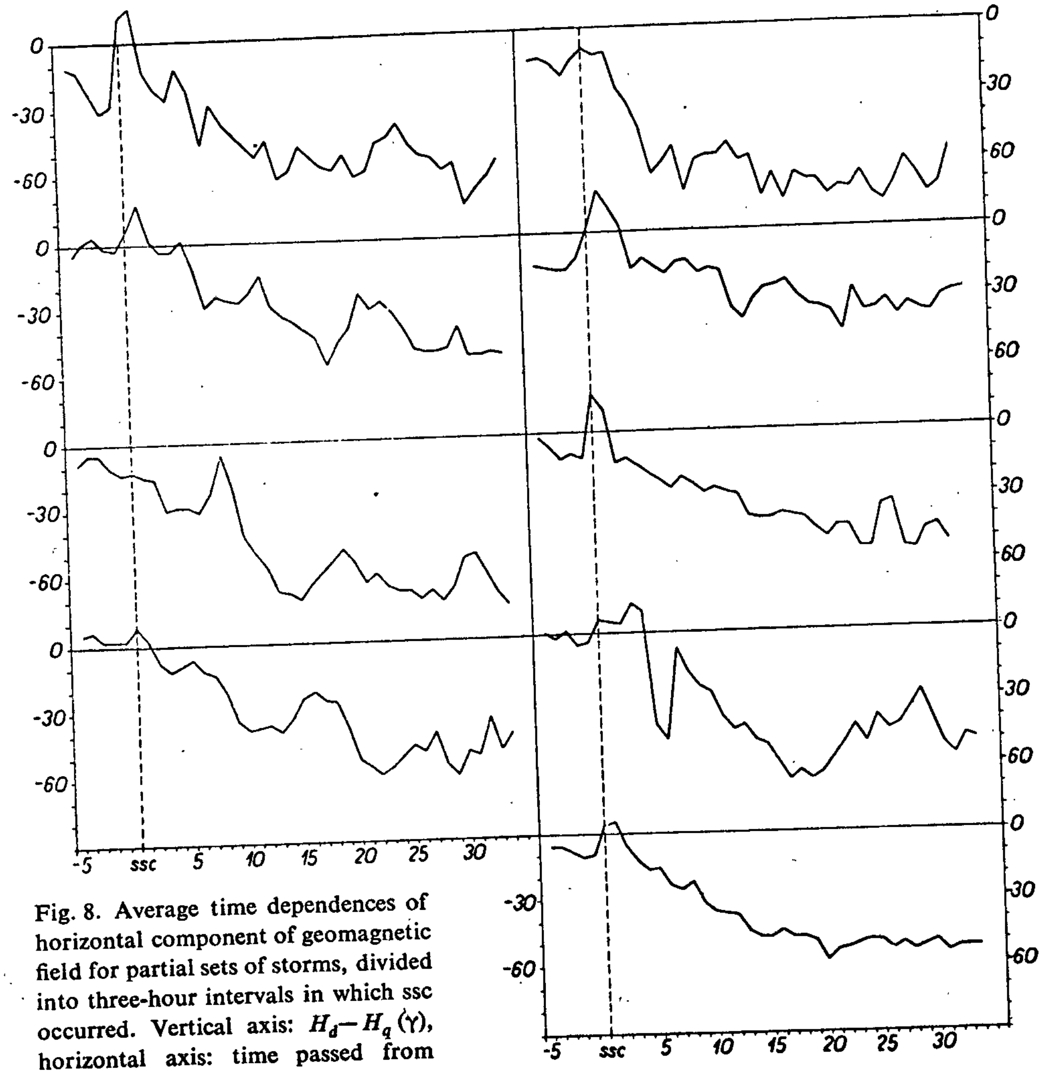

Fig. 8. Average time dependences of horizontal component of geomagnetic field for partial sets of storms, divided into three-hour intervals in which ssc occurred. Vertical axis: $H_d - H_q$ (γ), horizontal axis: time passed from ssc (hr).

Table III

*Statistics of occurrence of different main types of geomagnetic storms*

| Type | Number | % | Total | |
|---|---|---|---|---|
| | | | number | % |
| VP | 36 | 40 | 54 | 60 |
| OP | 15 | 17 | | |
| PP | 2 | 2 | | |
| V | 1 | 1 | | |
| O | 8 | 9 | 30 | 33 |
| P | 18 | 20 | | |
| VO | 4 | 4 | | |
| more complicated | 6 | 7 | 6 | 7 |

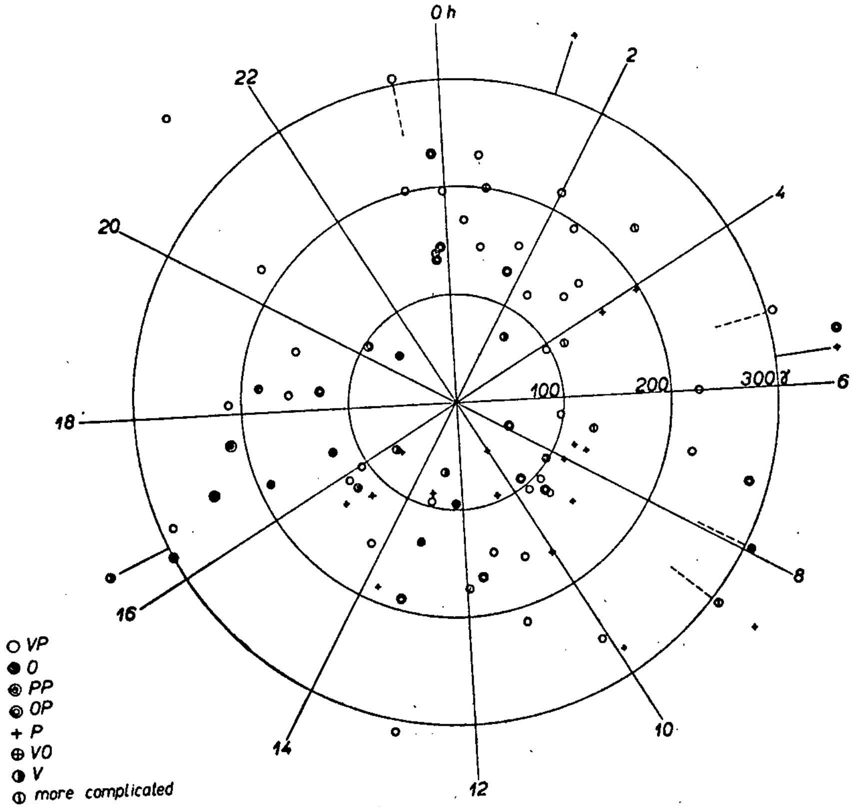

Fig. 9. Polar diagram of occurrence of geomagnetic storms used in attempt at new classification taking into consideration type of storm, moment of ssc and magnitude of maximum amplitude *H*.

consideration the type of storm, the instant of sudden commencement and the magnitude of the maximum amplitude of the horizontal component of the geomagnetic field during the storm.

On the other hand, if the occurrence of the different types is investigated separately, the P and O one-phase types show a tendency to occur only at a certain time of day (Fig. 10). This is also a proof that in the above classification not only possible local disturbing influences but also causes on a world-wide scale may play a part and that the classification of storms also has physical significance.

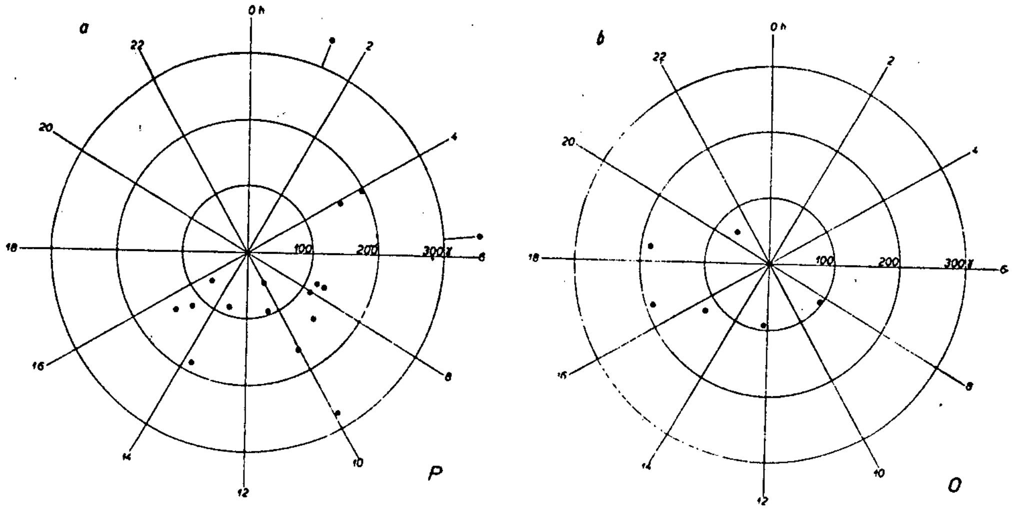

Fig. 10. Polar diagram of occurrence of one-phase geomagnetic storms a) type P, b) type O, taking into consideration moment of ssc and magnitude of maximum amplitude *H*.

## IV. ON THE QUESTION OF THE MECHANISM OF GEOMAGNETIC STORM DEVELOPMENT

The classification of phenomena occurring within the framework of geomagnetic activity has shown that storms represent a very pronounced group of disturbances. In order to be able to make use of the laws governing the phases of storms for studying the connection between solar and geomagnetic activity, the most fundamental of them should be pointed out here. At the same time one must not forget a brief definition of the different types of storms from the point of view of structure and geographical expression together with their theoretical conceptions.

### 1) Basic Classification of Storms

Geomagnetic storms are distinguished by several pronounced features. If we study their time dependence (Fig. 11), it can be included in the general characteristics of storms [2]. These are:

a) Sudden commencement, which is characterized by a relatively rapid growth in the magnitude of the horizontal component of the geomagnetic field, especially in low latitudes. The value of this increase is on an average around 30 γ and increases towards the equatorial region, where it attains maximum values. The rise time fluctuates around 2 minutes. However, the occurrence of a sudden commencement is not a rule for all storms. With so-called sc-storms it is observed all over the world but its magnitude varies from place to place. The sc also reaches higher values in the auroral zone on the illuminated side. At present the microstructure of the commencements of storms is the object of interest in a number of papers [31, 32].

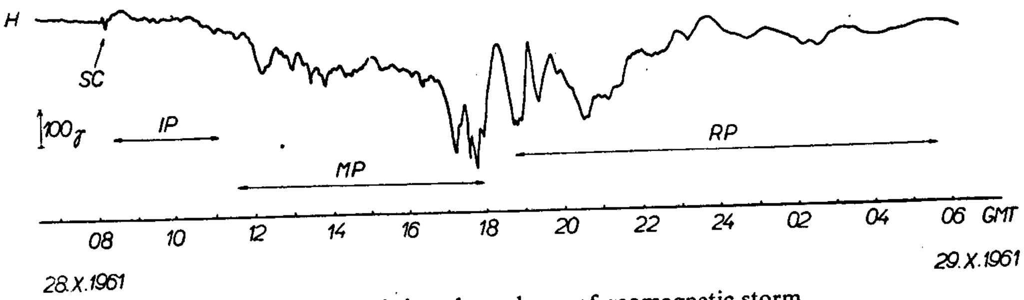

Fig. 11. Total time dependence of geomagnetic storm.

b) The initial phase of a storm is the interval lasting for approximately 2 to 8 hours after the sudden commencement. It is characterized by the fact that the *H* component maintains approximately its initial undisturbed value, slightly increased compared with the period before the storm.

c) The main phase is marked by a considerable decrease in the horizontal component compared with the initial undisturbed field. After reaching minimum the *H* component gradually returns but it is covered by strong storminess of the whole process; for a large part of this period, usually lasting 12–24 hours, there are large positive and negative changes which reach several hundred γ.

d) The return phase, as the last part of storm activity, is seen as a further gradual return of the *H* intensity to the original undisturbed value and a gradual quietening of activity (decrease in amplitudes of positive and negative changes). They last approximately 1–3 days while in the second part there is only a gradual return.

## 2) Types of Geomagnetic Storms from Aspect of their Geographic Expression

The records of the time dependence of the geomagnetic field confirm that geomagnetic storms can be divided into two basic types according to the laws governing their expression. The first group consists of world storms, which are accompanied by a general decrease (to a smaller extent an increase) in intensity of the geomagnetic field simultaneously over the whole Earth, both in the polar and in the equatorial regions. The second type are so-called polar storms or disturbances occurring both as negative and positive forms. Both types of storm are excited by the action of corpuscular radiation.

a) *World storms* are disturbances of the geomagnetic field of maximum intensity, where the fluctuation of the elements reaches values of up to thousands of $\gamma$. They take place over a period of several days. The main changes during a storm occur to a great extent simultaneously and similarly over the whole surface but of course the total dependence is disturbed by disturbances of a local character, particularly in higher latitudes, where there is also an increase in the amplitudes of irregular fluctuations. A typical world storm begins with a sudden commencement (sudden sharp increase in horizontal component – ssc) observed in 1 minute synchronously over the whole surface of the Earth, with maximum amplitude in the equatorial regions. Here, too, the storms occur in their purest form.

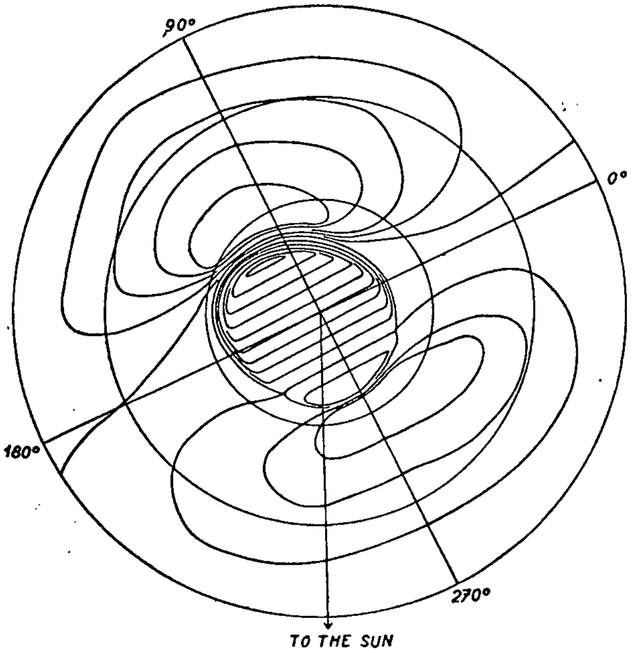

Fig. 12. System of streams produced in E-layer which formally explains field distribution during geomagnetic disturbance.

After the sudden commencement the storms then develop in phases as described above.

The average course of the storm is given by the storm variation $D_{st}$, to which three components of the disturbance field $D$ contribute; the field is described by the expression [33]

$$D = DCF + DP + DR . \tag{11}$$

The $DCF$ field is excited by the inflow of the corpuscular stream (sudden commencement + initial phase), $DP$ is the disturbance field produced in the polar regions (sudden fluctuations during main phase) and $DR$ represents the effect of a toroidal electric current.

b) *Polar storms* have maximum values not directly in the polar regions but in the zones of aurorae. This proves the connection between the two phenomena. Polar storms are characterized by the single occurrence or sequence of several sudden (increase or decrease) deviations from the undisturbed value, the most pronounced at the horizontal component. The intensity of the impulses decreases together with the distance from the polar regions in the direction of the equatorial region. In lower latitudes storms are apparent only in the form of a bay; for this reason they are sometimes called bay storms. Their annual time distribution has been found to be characterized by two maxima in periods of the equinox. The daily variation of the disturbances then exhibits interesting properties in that negative disturbances are produced during the night in auroral zones and positive disturbances during the day. However, many more negative disturbances occur than positive ones. In the middle latitudes this circumstance is not nearly so obvious.

The relatively rich material obtained for these disturbances permitted the proposal of a system of currents originating in the height of the ionospheric layer E [34] (Fig. 12), by means of which the observed field distribution during disturbances can be formally explained. The currents have a high density and flow along the auroral zones. While there exists only one current system above the polar regions, in the middle latitudes two vortices are formed; one runs anti-clockwise on the night and morning side of the Earth, and the other clockwise on the day and evening side. The absolute value of the current can reach up to hundreds of thousands of A.

### 3) On the Theory of the Causes and Origin of Geomagnetic Storms

The very complexity and irregularity in the course and other characteristic features of storm activity indicate that not even the finding of the actual physical conception of the model, which would satisfactorily explain all the natural phenomena taking place during storms, will be easy or without obstacles.

Research hitherto has basically followed two different lines, the difference consisting mainly in the conception of the properties of interplanetary space and of the charged particles moving along the Sun-Earth path.

α) The first conception is based on the assumption that in interplanetary space there exists no large magnetic field and that the ionized matter emitted from the Sun is not magnetic. This assumption is used in many theories starting out from hydromagnetic equations as well as in the classical theory of Chapman-Ferraro [35], which in addition assumed the negligible influence of interplanetary gas.

β) The second conception is based on the opinion that the ionized clouds emitted from the Sun are magnetized either by the total solar field or by local fields of the active regions. The particles move with a velocity of $10^8$ cm/sec and the flux is also electrically polarized; the electric field is of an order of $1-100$ V/cm and is very important for the creation of magnetic storms. The theoretical procedure is then based on a study of the motion of the individual particles.

Difficulties arise in the first group of theories if it is required to explain how a corpuscular cloud penetrates into the magnetic field of the Earth; it is equally difficult to explain the formation of a toroidal current. Also the 27 daily variations of cosmic radiation are in conflict with the fact that interplanetary space has no magnetic field. The incorrectness of this opinion was proved by cosmic radiation measurements by means of satellites. The Forbush decrease in intensity of cosmic rays was recorded at large distances from the Earth due to the influence of the magnetic field present there, which is in considerable disagreement with the second conception.

Let us now deal with the basic features of some models which try to explain the different phases observed during storms. Recently theoretical research has taken into consideration the latest observational data on the state of interplanetary space and the exosphere, which has led to more exact physical models.

The starting point for all more recent theoretical models of geomagnetic storms is the assumption of an electrostatically neutral corpuscular stream propagating from the Sun to the Earth. However, opinions differ as to the effect of such a stream on the magnetic field and this has led to the elaboration of different models.

a) *The model based on the effect of a dipole magnetic field on the moving conducting medium* [35] assumes that a cylindrically shaped cloud of corpuscular gas with sharp boundaries approaches the geomagnetic field. If the medium is conductive, then by its approach to the magnetic field electric currents are induced in it which prevent the magnetic field from penetrating into the interior of the corpuscular cloud. In addition mechanical forces of a repulsive character are produced between the dipole and the conductive medium and try to prevent the cloud from further movement. Since the conductive medium is not rigid, these forces cause the surface of the corpuscular stream to begin to deepen and a cavity to be formed in it. The lines of force between the Earth and the front of the cavity densify results in an increase in the horizontal component of the geomagnetic field, observed during the initial phase of the geomagnetic storm. The increase in the horizontal component $\Delta H$ at a sudden commencement, which is related to the dimensions of the cavity and the flux moment $nmv^2$, is described by the expression $H_0/8z^3$, where $H_0$ is the equatorial value of the horizontal component on the surface and $z = (H_0^2/8\pi E)^{1/6}$ represents the distance between the peak of the cavity and the centre of the Earth. Further, the energy $E = H^2/8\pi = nmv^2$, where $H$ is the geomagnetic field in the peak of the cavity, $n$ the density of the particles, $m$ the mass and $v$ the velocity of the corpuscles. The main phase, seen as a decrease in the horizontal component, can be explained by the production of a closed toroidal electric current around the Earth, flowing in the equatorial plane. This current is formed as a consequence of the electric field produced by volume charges which collect on the evening and morning side of the cavity as a result of the separation of the charged particles by the geomagnetic field. Only protons are of importance for the current due to their large gyration radius.

b) *The model explaining the origin of geomagnetic storms by the effect of the electric field of a corpuscular cloud* [36] is based on the assumption that the particles of electrically polarized gas emitted by the Sun carry with them the magnetic field frozen into a highly conductive medium. When the beam of ionized gas moves an electric field is produced described by the relation $\mathbf{E} = -(1/c)[\mathbf{v} \times \mathbf{H}]$, where $\mathbf{v}$ is the velocity of motion of the beam and $\mathbf{H}$ is the field frozen into the beam. When the flux reaches the Earth's magnetic field and the separation of the positive and negative particles begins, the influence of the electrons flowing round the Earth in the eastern direction is seen in the form of a sudden commencement. The motion of particles in a combined electric and magnetic dipole field consisting of circular motion superposed on translational motion was calculated. The velocity of particles behaving in this manner is given by

$$\mathbf{v} = -(c/eH^2)[\mathbf{H} \times \{e\mathbf{E} - \mu \operatorname{grad} H - m(\mathrm{d}\mathbf{v}/\mathrm{d}t)\}]\,, \tag{12}$$

where $\mu$ defines the ratio of the kinetic energy of the particle to the magnetic field. The motion of particles forms a volume charge in certain regions, which leads to the creation of toroidal currents. When looking from the north pole the left-handed current forms a sudden commencement while the creation of the main phase of a geomagnetic storm is ascribed to the right-handed current (due to the eastern motion of the electrons).

The interval between the sudden commencement and the main phase of a geomagnetic storm was not explained by this model. The following model attempts to do this.

c) *The model taking into consideration a shock wave* in the origin of geomagnetic storms is based on the assumption that apart from the corpuscular stream a shock wave, which has its source in the ejection of particles from the Sun [37], also plays a role in the storm mechanism. Such a wave contributes to the separation of the charges and thus also to the causes of currents flowing in the atmosphere and manifest as a sudden commencement. It follows from the theory of strong shocks that the velocity of the gas borne along by this wave is only three-quarters of the velocity of the shock wave. Therefore, the corpuscular stream reaches the Earth with roughly a nine-hour lag (Fig. 13). The particles of this stream can therefore penetrate into the depths of the geomagnetic field and thus also into the forbidden Störmer regions since they enter the field already disturbed by the wave. The particles caught in the geomagnetic field move primarily along the geomagnetic lines of force but simultaneously they drift according to their polarity to the east or west while an electric current is produced which flows in the western direction (main phase). This current gradually decays due to the absorption of the particles in the Earth's atmosphere, which also explains the decay of the geomagnetic storm.

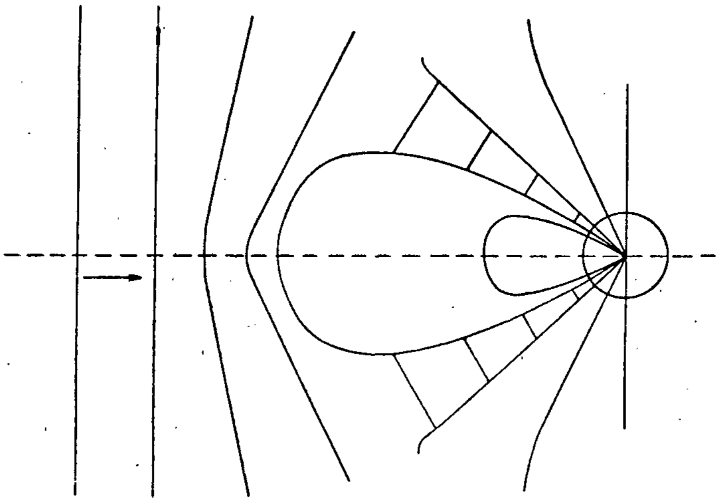

Fig. 13.

d) *The hydromagnetic model* is characterized by the interaction of solar plasma with the geomagnetic field and the method of propagating the effects towards the Earth. It is assumed that due to the influence of the pressure of solar plasma the Earth's dipole field is limited by regions up to a distance of approximately 10 Earth's radii [38], where the magnetic pressure is already lower than the pressure of the solar plasma. When the plasma suddenly ejected from the Sun collides with the geomagnetic field processes occur which result in the geomagnetic storm on the Earth's surface. The sharp front of the solar plasma cloud is formed by the influence of the interplanetary magnetic field and the gas present there.

The basic hydromagnetic equation defining the relation between the velocity $\mathbf{v}$ of the particles, arriving at the region of the geomagnetic field on sudden ejection from the Sun, and the intensity of the magnetic field is given in the form [38]

$$\varrho\, \mathrm{d}\mathbf{v}/\mathrm{d}t = -\left(\mathbf{P}_1 + \mathbf{P}_2 + B^2/2\mu_0\right) + (\mathbf{B}\nabla)\,\mathbf{B}/\mu_0\,, \tag{10}$$

where $\mathbf{P}_1$ gives the pressure of the tenuous plasma in the field $\mathbf{B}$, $\mathbf{P}_2$ is the equivalent pressure of the injected particles and $B^2/2\mu_0$ is the magnetic pressure. The different phases of the storm can then be ascribed, as has been elaborated in detail, to the partial expressions of the interaction resulting in the production of pressures propagating towards the Earth in the form of hydromagnetic waves.

The sudden commencement of a geomagnetic storm is ascribed to the impact of solar plasma with the sharp front on the geomagnetic field. This disturbance propagates towards the Earth in the form of a hydromagnetic wave.

The initial phase of a storm is caused by the increase in pressure of the constantly inflowing solar wind on the magnetic field of the Earth. The main phase is obviously due to the pressures which are produced in the Earth's magnetic field by the trapped protons of solar origin. A considerable part of the pressure is caused by the centrifugal force of the trapped particles at their oscillation along the lines of force during passage through the equatorial plane (Fig. 14).

A geomagnetic storm ends with the phase of decay, which due to its limited duration requires the quietening of most of the trapped particles in a period of about one day. This process corresponds to the mechanism of charge exchange between the active protons and the neutral atoms of atmospheric hydrogen.

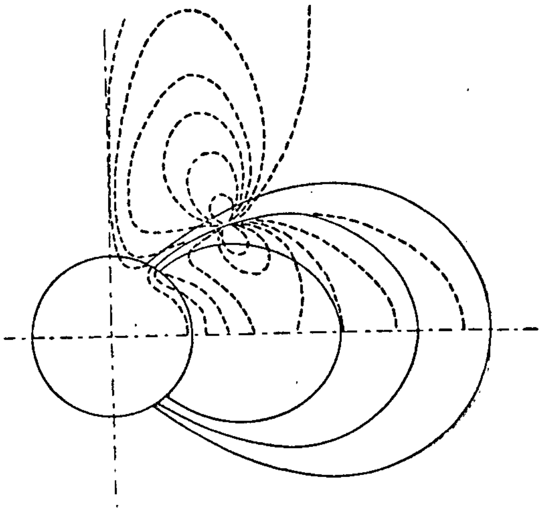

Fig. 14.

e) *The model of a geomagnetic storm, which is based on a combination of the effect of the homogeneous electric field of the volume charge and the system of irregular fields,* aims at explaining the mechanism of the penetration of solar ions into the geomagnetic field [39]. Existing theories explaining the origin of geomagnetic storms by the effects of the corpuscular stream have in most cases not been able to explain how the particles can penetrate into the Earth's magnetic field. The increase in the horizontal component (at a sudden commencement) cannot be caused by a toroidal current outside the geomagnetic field but by a mechanical force acting on the electrically conductive gas at a distance of several Earth's radii in the direction of the Earth. On the other hand, during the main phase the mechanical force acts away from the Earth. The effect of such a force leads to hydromagnetic processes in regions at a distance of several hundred km from the earth due to the moving gas in the magnetic field. The consequence of such processes is that the lines of force of the magnetic field, frozen into the conductive medium, are borne away from the Earth and form an elongated cylindrically shaped formation, "a magnetic tail", on the unilluminated side of the Earth (Fig. 15). The continuous acceleration of the ions in this "tail" against the Earth by the electromagnetic forces leads to a total decrease in the horizontal component of the geomagnetic field – the main phase of the storm.

The theory is based on a study of the motion of two forms of gas – ion-electron plasma and neutral atomic gas. The application of such a study shows that at distances of several hundred km from the Earth's surface the disturbances are transported by means of the hydromagnetic waves, while in lower regions the dispersion medium causes the disturbances to be transported by means of diffusion. This model permits an explanation of some important effects connected with the course of a geomagnetic storm, including processes in the radiation (Van Allen) belts, counterglow, daily variations in cosmic rays etc.

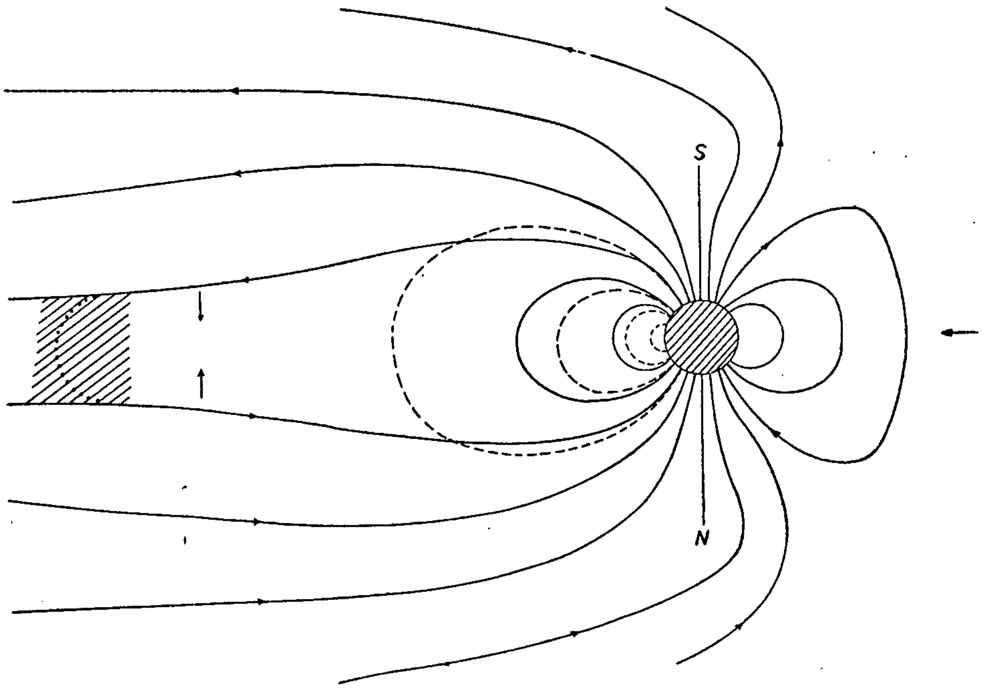

Fig. 15.

The principal conceptions of the above models represent a brief survey of the basic and latest theoretical conceptions as to the conditions necessary for the creation of the mechanism of geomagnetic storms. The very fact that a series of models exists in parallel, each of which is physically substantiated in a different way, indicates that it has not yet been possible to arrive at a completely satisfactory conception which would be in keeping with the physical nature of storms and would also explain their partial features and individual pecularities. Greater uniformity could certainly be achieved by studying other parameters which have not yet been sufficiently investigated but which might play an important role in the correct physical conception of the model.

One important way of refining such parameters is indoubtedly a study of the conditions and causes of the emission of solar geoactive corpuscular radiation. In this the above models differ quite considerably; some do not take the question of the emission mechanism into consideration at all and others make obviously very simplified assumptions although it can be expected that the parameters by which the corpuscular stream enters into interaction with the geomagnetic field will to a great extent be given by the mechanism of its origin on the Sun. The determination of the correct relations between solar and geomagnetic activity is a contribution towards finding the most probable parameters.

## V. CONNECTION BETWEEN PROCESSES ON SUN AND GEOMAGNETIC ACTIVITY

The connection between solar and geomagnetic activity has been known for more than a century but still no unified conception has been reached as to what is the source of geoactive corpuscular radiation. Different papers treating the various epochs of the solar cycle have dealt with all the expressions of solar activity and a definite but often unsatisfactory connection has been found. For this reason a detailed analysis of all the expressions of solar activity had to be made and their inter-relation determined when elaborating a method for the prognosis of geomagnetic storms.

Investigations into active centres consisting of successive expressions of solar activity have shown that on its passage through the central solar meridian (CMP) one and the same active region often has different consequences corresponding to its phase of development, and that the geoactivity (i.e. the following increase in geomagnetic activity excited by corpuscular radiation) depends on their instantaneous state at the time of the CMP. It was also found that the connection between active regions and geomagnetic storms is not a simple affair since it depends on the processes taking place in their surroundings and on the mutual configuration.

These questions became the object of our investigations. Here we give some of the most important conclusions with a view to contributing towards a clarification of the above relations which have been the object of geophysical research for a number of years. Our attention will successively be paid to all main phenomena occurring in active centres both as isolated effects and taken complexly.

Since the geoactivity of a solar active centre substantially depends on its phases of development, let us first deal briefly with the chronological sequence of events on the Sun from the point of view of their development.

### 1) Solar Activity – Phases of Development of Active Centre

Each active region is preceded by the formation of a local magnetic field. Bright small facular and floccular fields appear and gradually increase their extent. Then spots are formed but these accompany the life of the active region for a relatively short time. They gradually become larger and the magnetic field becomes complex. If the development of the group of spots reaches a certain degree flares and surges begin to occur in it and filaments (prominences) appear. The chromospheric structure shows that in the chromosphere there is a very complex magnetic field which corresponds to a certain extent to the photospheric field. During flare activity in the active region more filaments are produced while those already existing here often change their direction and shape or even disappear (activation of filament). Others are "extracted" from the region, and straighten if they were previously arc-shaped. Sometimes these changes occur during flares while at other times this occurs in a broad time interval around the flare. For the filament to disappear it is not necessary that it be near to a flare. Distant filaments also often disappear. According to the mechanism explaining the existence of a filament, which was given in Chap. I, it can be assumed that their disappearance may occur when the magnetic field which kept them in equilibrium is at least temporarily compensated. Such compensation occurring in the period of changes in the magnetic field can be expected rather in those parts of the active region where the magnetic field strength is lower than that of weaker disturbing fields. It can be admitted [40] that filaments disappear as a consequence of changes in the local magnetic fields; one cannot, however, neglect the influence of the total field which adds up with the local fields.

In the next phase the filament moves away from the active region and different basic configurations can occur. From the behaviour of the free part of the filament we can deduce that it is under the influence of the magnetic fields of the surrounding spots. Sometimes the filament may decay [41] or join up with a neighbouring filament.

If so-called spot prominences are produced by the condensation of the coronal masses on the lines of force of the strong local magnetic fields already formed directly above the active centre, then the above interpretation of the disappearance of the filament due to compensation by the field can be applied.

Filaments often last much longer than the period of spot occurrence; they remain in the floccular field and are gradually shifted to higher heliographic latitudes. Finally, the floccular field disappears entirely and only the filament remains. Apparently the rotation causes the filament to turn into the approximately parallel direction while the filaments originally occurring in the spot zones had the meridional direction.

## 2) Geomagnetic Activity and Sunspots

When investigating the relations between these phenomena it was generally found that in the same way as the occurrence of sunspots falls into an eleven-year period so geomagnetic storms are subject to analogous laws. This fact has become the starting point for many scientists in their search for inter-relations. The average values of the main characteristics (number, area and relative number) of spots were primarily compared with different geomagnetic indices. It was found statistically that a few days after the CMP of the spots there exists a definite probability of the occurrence of geomagnetic storms. A comparison of the individual cases, however, showed that not all spots are followed by geomagnetic storms. Nor was the opinion confirmed that there exists a direct connection for the largest groups. Such groups are to a great extent the seats of other expressions of solar activity so that the conception taking into consideration the geoactivity of spots might probably be more justified. However, not even in this case is the connection given between spots and geomagnetic activity satisfactory.

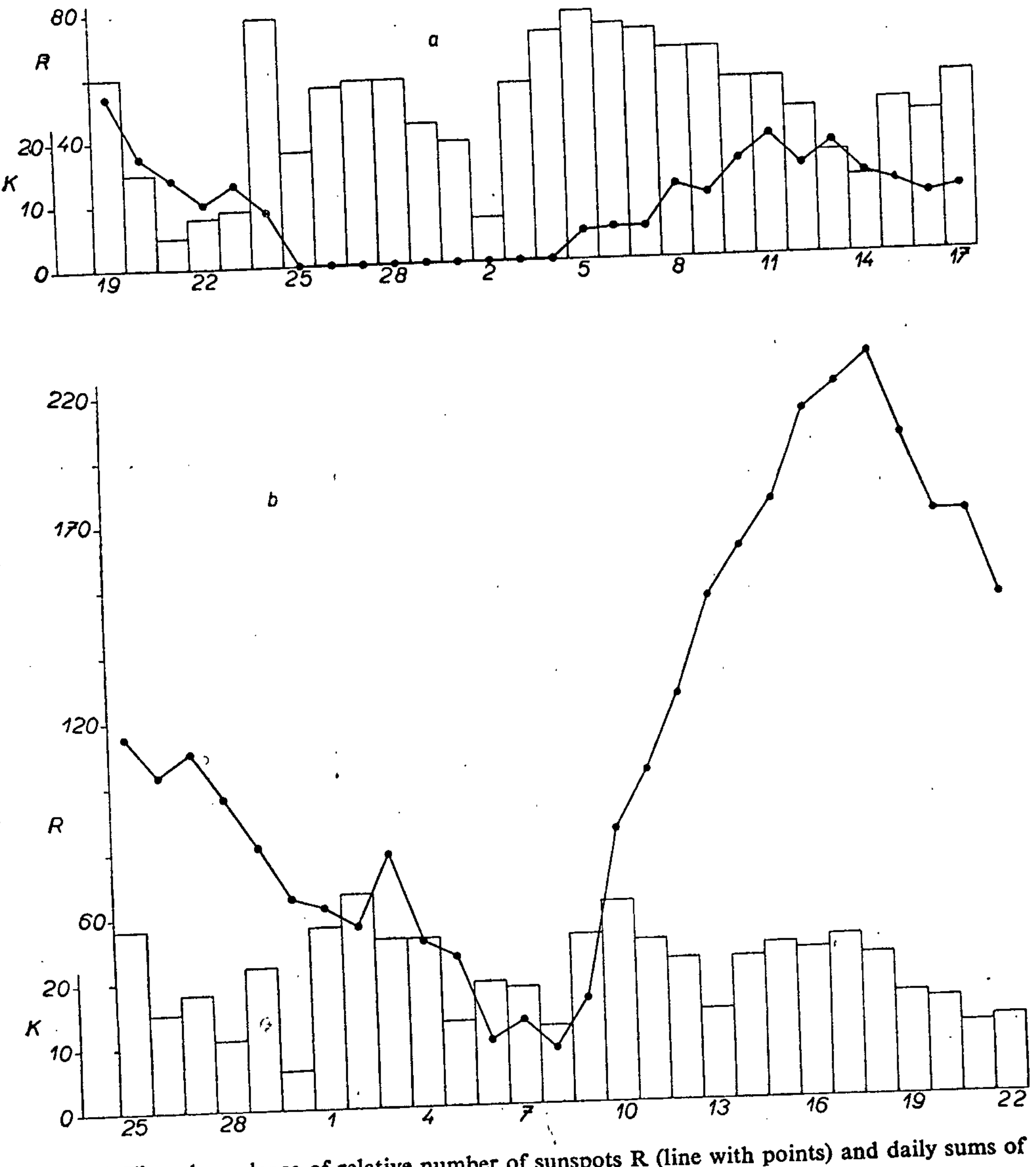

Fig. 16. Time dependence of relative number of sunspots R (line with points) and daily sums of *K*-index of geomagnetic activity in period a) 19. II.—17. III. 1952, b) 25. IV.—22. V. 1951.

Let us now deal in greater detail with the question of whether spots by themselves can be geoactive. We compared the curves of the daily values of the relative number of solar spots [43] and the daily sums of the $K$-indices [44], characterizing the geomagnetic activity [45]. In a number of cases it was clearly seen that geomagnetic disturbances are produced even in those epochs when spots did not occur on the Sun at all and, vice versa, there is often a decrease in geomagnetic activity even at large spot activity. Examples of the two above cases are plotted in Fig. 16. It is seen from Fig. 16a that in the epoch of zero relative number (25. II. to 4. III. 1952) there was an increase in the $K$-indices. On the other hand, they decreased around 19. V. 1951 (Fig. 16b) when the relative number was very high.

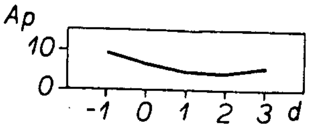

Fig. 17. Average time dependence of geomagnetic activity after CMP of groups of spots, which were not accompanied by central filament.

Such investigations would not in themselves be proof because the relative number does not take into consideration the position of the spots on the solar disc. However, due to the conception of the radial propagation of corpuscular radiation one can expect the distance between the group of spots and the centre of the disc to be the decisive factor. For this reason we investigated the chosen very quiet, internationally determined intervals of geomagnetic activity [46] for the years of a fall in solar activity (1950 to 1953) from the period when the zones of sunspot occurrence approach the equator and thus when the individual groups of spots may occur more frequently in the centre of the disc. A quiet interval can thus be expected when there is no geoactive source in activity on the Sun. Table IV shows, however, that in 90% of the cases the quiet intervals in 1950 were preceded by the CMP of sunspot groups [47], which is a quite convincing proof that spots cannot be geoactive. With the decrease in solar activity the percentage of quiet intervals preceded by the CMP of sunspot groups also decreases but this is the obvious consequence of a decrease in the number of sunspot groups in the direction of the minimum of solar activity. It thus follows that a large number of sunspot groups is followed by a pronounced decrease in geomagnetic activity, i.e. these spots cannot be the source of geoactivity.

Comprehensive material was elaborated by the method of superposed epochs during

Table IV

*Very quiet intervals*

| Year | Number of intervals | | % |
|---|---|---|---|
| | total | with preceding spots | |
| 1950 | 19 | 17 | 90 |
| 1951 | 11 | 8 | 73 |
| 1952 | 13 | 7 | 54 |
| 1953 | 17 | 5 | 29 |

the 1937–1958 period in order to reach a definite decision on the question of the geoactivity of spots. Zero day was taken to be all the CMP of isolated groups of spots regardless of type, whether with or without flares; these groups were not accompanied by a filament passing through the centre of the solar disc. Altogether 110 cases were investigated to find the average course of the geomagnetic activity expressed by the values of the *Ap*-index [48] in the critical period after CMP (Fig. 17). It is obvious that the activity in this period is very low and, moreover, shows a slight decrease on the +1 and +2 days. Since it might be objected that this statistical treatment could smooth out the possible geoactivity of the most important sunspot groups, the set of most important and medium sunspot groups was treated individually. Not even in these most favourable cases did a geomagnetic disturbance occur, as is seen in Fig. 18. These results showed quite definitely that spots in themselves cannot be geoactive. The connection between spots and geomagnetic storms found by some earlier statistical papers can easily be explained by the fact that the methods used then did not take into account the occurrence of other expressions of solar activity in the spot regions.

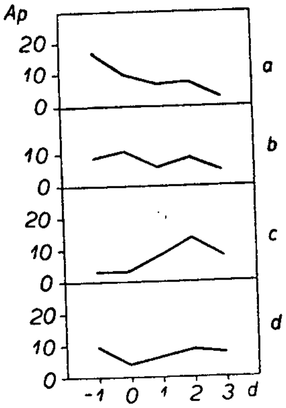

Fig. 18. Time dependence of geomagnetic activity after CMP of four selected largest groups of spots which were not accompanied by central filament. Date, type and heliographic latitude at CMP of group of spots: a) 12.VIII.1940, F, 7°N, b) 20.VIII. 1940, F, 9°N, c) 14. IV. 1943, E, 14°S, d) 17. VI. 1958, E, 15°N.

### 3) The Question of the Geoactivity of Flares

Shortly after the discovery of flares the first conclusions were drawn that strong flares are connected with geomagnetic storms [49]. The values they gave for the velocity of propagation of corpuscular streams are still recognized. Later a statistical verification was made of the results where it was found that there is a certain dependence of the geoactivity of flares on the distance from the centre of the solar disc; according to this the angular aperture of the cone in which the corpuscular rays are emitted from the flare, would be roughly 90° [3, 50]. As material has accumulated great attention has been paid to this question in other papers. The results obtained for the direct connection between flares and geomagnetic storms, however, showed that the correlation is not convincing [51]. The question of why a large number (around 50%) of flares, even when conveniently situated, do not appear to be geoactive is still unanswered. Papers have also appeared which doubt any connection [52–54]. Sometimes the geomagnetic disturbance is ascribed to flares occurring on the edge of the disc.

In our work we concentrated on a detailed investigation of the main aspects of the connection between flares and geomagnetic activity.

The material from the IGY period was elaborated statistically using the method of superposed epochs [55]. We found that even the commonly used statistical methods produce results which cannot be satisfactorily explained by assuming a direct connection between flares and geomagnetic activity.

An analysis of the results led to the conclusion that the geoactivity of flares, particularly of those with smaller importance, should be understood as the geoactivity of the active regions in which these flares occurred. A statistical evaluation was then made by an analogous method [57] of all flares observed in 1937 to 1956 and contained in the Catalogue of large chromospheric flares [56].

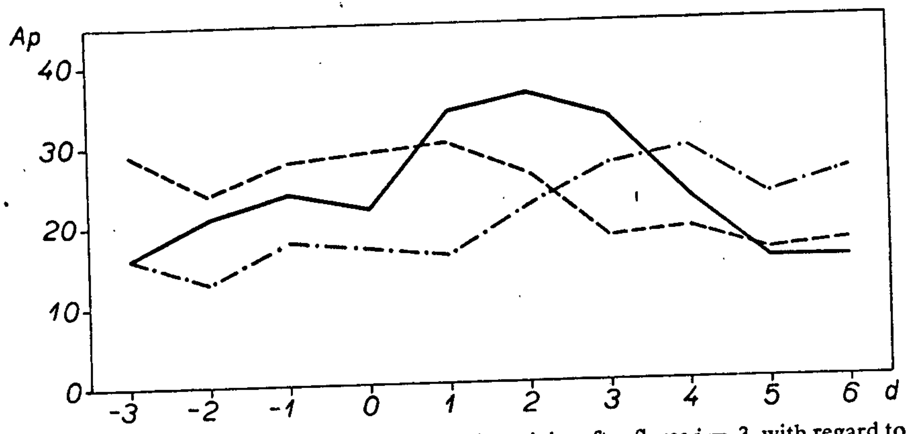

Fig. 19. Average time dependence of geomagnetic activity after flares $i = 3$, with regard to distance of flares from CM. Full line — central flare (29°E—29°W), dashed line — western flare (≧30°W), dotted-and-dashed line — eastern flare (≧ 30°E).

Figure 19 shows that although medium flares are followed by a pronounced increase in geomagnetic activity the analogous increases for eastern and western flares are time displaced so that the maximum for western flares is earlier and that for eastern flares is later. This fact, together with other proofs, led to the above conclusion that there exists only an indirect connection between flares and geomagnetic activity. We also found that even if a direct connection is admitted, the value of the angular aperture is smaller than 60°.

It is also clear from [57] that the mean value of the time interval between a flare and the following geomagnetic storms has only formal significance and depends on the length of the period to which we confine ourselves in ascribing the geomagnetic storms to the different flares (Fig. 20). This indicates the random distribution of geomagnetic storms occurring after flares and does not give the typical mean value of the interval.

*Two conceptions of how to understand the connection between flares and geomagnetic storms* were proposed for a satisfactory explanation of all the dependences found statistically:

1) Flare activity in the active region, or any other source of geoactivity of the active region in which a large flare occurred, lasts for a long time, during which the active region may pass through the central meridian. If the conditions for the emission and direction of a corpuscular stream are fulfilled in this critical position, then this active region may be followed by an increase in geomagnetic activity with which the flare in question is not directly connected.

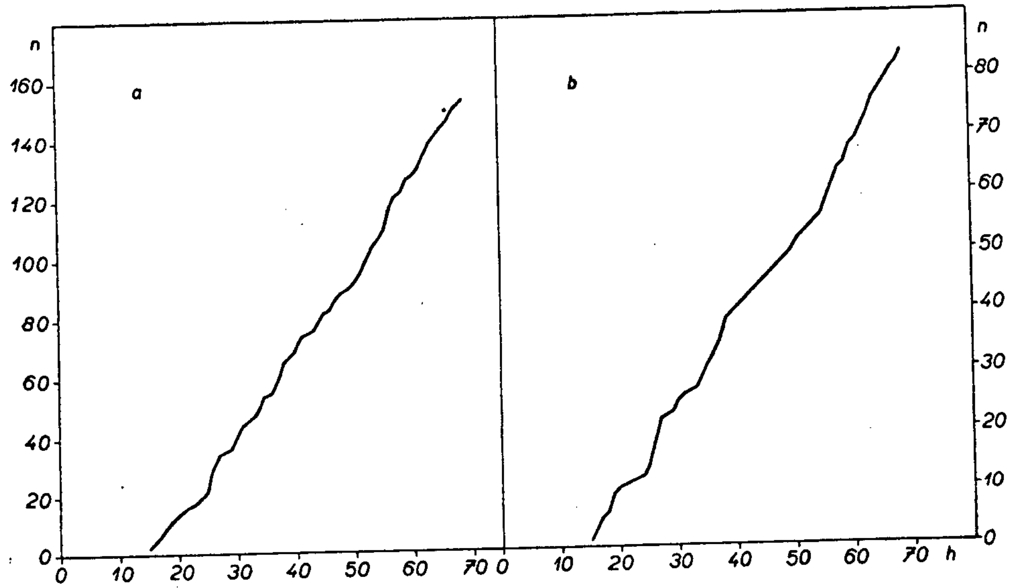

Fig. 20. Summation curves for set of time intervals between large flares and following geomagnetic storms. a) all flares, b) central flares (29°E—29°W).

2) The increase in chromospheric activity, which was seen inter alia as the occurrence of a large flare in some active region at a distance from the CM, need not remain limited only to this active region and its immediate neighbourhood but can appear more or less simultaneously in more distant parts of the solar surface. If such an increase takes place also in the active regions which are just on the CM, then such regions may be followed by an increase in geomagnetic activity with which the flare in question is not directly connected.

The above statistical results are in keeping with the individual investigations into the geoactivity of the different active regions with rich flare activity. Four isolated active regions were chosen (this means that during their passage over the solar disc practically no other flare activity occurred on the solar surface) and the results of observing flares in them were classified with the course of the geomagnetic activity during passage over the solar disc [58]. Despite the fact that throughout this time a series of large flares occurred in the active regions, the geomagnetic activity increased markedly only in the expected interval after the passage of the active region through the central meridian (Fig. 21). From this it is clear, inter alia, that the influence of flares might be seen (if it exists) only in the immediate neighbourhood of the CM; thus conceptions ascribing geomagnetic storms to flares on the edge of the disc are quite unjustified.

Previous papers paid particular attention to how flares are reflected in geomagnetic activity; this means that the zero day in the method of superposed epochs was the day of occurrence of a flare. A possible connection can be verified, however, in the opposite direction, i.e. whether an increase in geomagnetic activity is preceded by a flare (zero day in the method of epoch displacement is the day of increased geomagnetic activity).

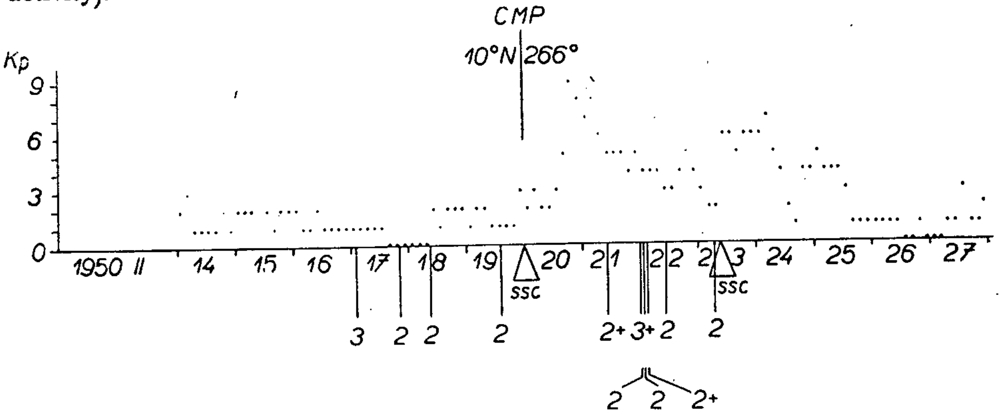

Fig. 21. Time dependence of geomagnetic activity (points) around CMP of active region with occurrence of strong flares (vertical lines with notation of flare importance).

With this in mind a statistical analysis was made of the solar situations preceding sudden commencements of geomagnetic storms (ssc), which also contains an elaboration of the occurrences of flares between these commencements in 1957–60 [40]. Only those ssc were chosen for which 100% observation of flares was ensured in an interval of 28 to 38 hours before an ssc. This 10-hour interval was chosen on the basis of the results of investigations which will be discussed in the next chapter. The investigations covered flares of all importances from 1– to 3+, which occurred in ±10° from the CM. The percentage of the number of cases when no such flare occurred before a sudden commencement was calculated. Table V shows that a geomagnetic storm occurred on an average in 45% of the cases without being preceded by a flare.

Due to the problematical character of the connection between flares and geomagnetic activity, which is clear from the statistical papers just discussed, it can be deduced that the increase in geomagnetic activity observed sometimes after flares could actually be explained by the geoactivity of other expressions of solar activity occurring in the active regions together with flares or possibly the geoactivity of expressions occurring on the CM synchronously with the flare which is at some distance from the CM.

A partly complex procedure was therefore adopted in investigating the influence of flares; not only flares but also filaments about whose connection with geomagnetic activity positive conclusions had been reached (see paragraph 4), were taken into consideration. The different configurations of flare and filament were thereby considered. Material was elaborated from 1950—1959 [59] for which the method of superposed epochs was used to determine the average variation of the *Ap*-indices around zero day (all days with the occurrence of a strong flare $i = 3$ or 3+ at successive distances of 10°, 20°, and 45° from the CM were chosen as zero day), in all 48 cases without the occurrence of a central filament (i. e. one, of which a certain part would pass through the centre of the solar disc). It was found (Fig. 22) that after the occurrence of flares without the presence of a central filament no increase in geomagnetic

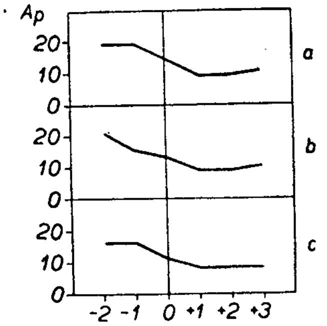

Fig. 22. Average time dependence of geomagnetic activity after occurrence of flare without presence of filament on centre of solar disc, taking into consideration distance of flare from CM, a) max. ±45°, b) max. ±20°, c) max. ±10°.

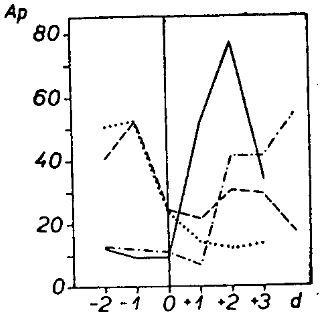

Fig. 23. Average courses of geomagnetic activity after occurrence of flares (max. ±45° from CM) in simultaneous presence of filaments. ——— filament on disc centre on same day as flare; ...... filament preceded (1—2 days); —.—. filament followed (1—3 days); — — — one filament preceded, other followed.

Table V

| Year | Number of geomagnetic storms not preceded by any flare |
|---|---|
| | % |
| 1957 | 30 |
| 1958 | 54 |
| 1959 | 46 |
| 1st half 1960 | 50 |
| mean value | 45 |

activity occurred; on the contrary, a slight decrease is observed. This is proof that there was no geoactive source in activity at the time in question and therefore the flare itself is not geoactive.

Quite different results were obtained when zero day was taken to be the day on which there was a flare at a maximum distance of ±45° from the CM but a central filament occurred, as is dealt with below. On the basis of 23 cases we distinguished four basic situations as a function of the time configuration of the flare and filament: a) the passage of the filament through the centre of the disc occurred on days of flare occurrence, b) the passage of a filament occurred just before a flare (roughly up to 1–2 days), c) the passage of a filament occurred just after a flare (max. 1 to 2 days), d) two filaments passed through the centre, just before and after a flare. The method of superposed epochs was used for all these four situations to obtain the average courses of the geomagnetic activity (Fig. 23) from which the following conclusions can be drawn:

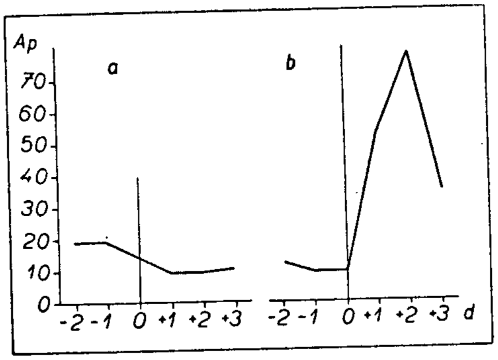

Fig. 24. Average time dependences of geomagnetic activity after occurrence of flares at max. distance of ±45° from CM a) without presence of filament on centre of solar disc, b) in presence of filament on centre of solar disc.

After the simultaneous occurrence of a flare and a central filament there is a pronounced increase in geomagnetic activity. In other cases the increase in geomagnetic activity is governed by the passage of the filament through the centre of the disc so that the maximum of the increase is time displaced in keeping with the time displacement of the passage of a filament from that of a flare. The geoactivity of the opposite solar situations is shown in Fig. 24.

Apart from this, individual investigations of the same question on a set offlares of homogeneized importances gave analogous results [60] confirming the fact that flares are not the direct source of geomagnetically effective corpuscular radiation.

### 4) Filaments and Corona – Their Geoactive Effects

Filaments – prominences – occur in the external solar layers above the photosphere, in the chromosphere and in the inner and middle corona; in the case of rising filaments they sometimes penetrate to the outer corona. Since it can be assumed that they are produced by the condensation of coronal matter along the lines of force of the local magnetic fields, leaving the photosphere, the structure of such fields can be deduced from their shape. At the same time prominences give a conception of the arrangement of the magnetic fields in the direction perpendicular to the solar surface while filaments and the fine structure of the chromosphere indicate the magnetic fields distributed parallel to the surfaces of the Sun.

On the basis of the relation of filaments to the surrounding magnetic fields we classified filaments into three groups [6, 61], which proved to be very useful in investigating the geoactivity of filaments. It was later found that this classification can be made in keeping with the development of filaments [6, 62] and therefore we give here the different types in the order of the phase development of the filament.

1) *Bound Filaments.* These are the youngest type of filaments occurring directly in the active regions and, as is clearly shown by their shape, they are under the influence of the local magnetic field. They persist in the active region without any great changes until they more or less suddenly become type 2 or gradually become type 3.

2) *Unstable Filaments.* Active, eruptive and disappearing filaments belong here, in the order according to the suddenness of the changes occurring in them. They occur again in active regions, not necessarily directly in the sunspot groups but always under the influence of the local magnetic field, the basic time changes of which are, we assume, the actual cause of instability of the filaments of this type.

3) *Free Filaments.* These include all filaments occurring clearly outside the active region which are thus not under the influence of local magnetic fields. They are filaments of the oldest phase of development which were produced in the active region as type 1 and outlasted the period characterized by sunspot and flare activity in which there occurred the strongest time changes in the magnetic field. In this period they begin to move gradually further away from the active region in the direction of the poles and to take up a position roughly in the direction of the solar parallels.

To the different types of filaments defined by our "magnetic" classification, one can ascribe*) different types of prominences according to the "motion" classification [63]

Table VI

*Classifications of different types of filaments-prominences*

| Classification | | |
|---|---|---|
| Magnetic | Motion | Morphological |
| 1. Bound filaments | electromagnetic prominences | particularly prominences of type III a)—c) and less active type I a)—c) |
| 2. Unstable filaments | eruptive prominences | particularly prominences of type II a)—b) and more active type of I a)—c) |
| 3. Free filaments | chaotic prominences | some prominences of type V |

---

*) If the filaments in question were observed on the solar limb as prominences.

or the classical "morphological" classification [64], based on quite different principles (Tab. VI).

The geoactivity of filaments – prominences – has already been investigated in a number of papers [65–67]. A certain connection between filaments and geomagnetic activity was statistically proved in the period before the minimum of solar activity, and this was explained by the fact that filaments could be the source of slower corpuscular streams exciting smaller geomagnetic storms with a gradual commencement, repeating after 27 days as a consequence of solar rotation. However, papers have also appeared which, on the basis of statistical methods, refute such a connection [68–71].

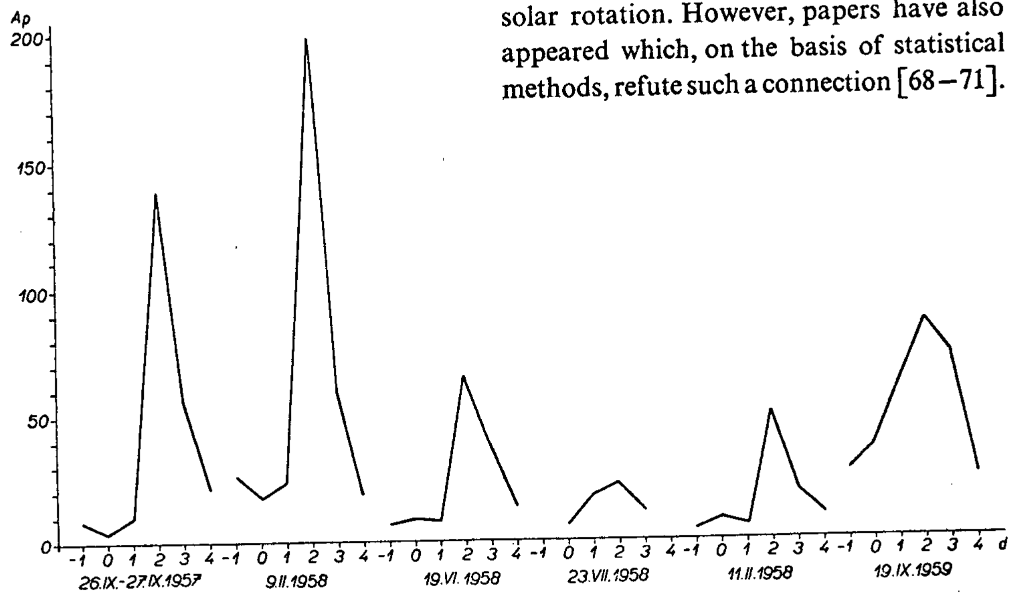

Fig. 25. Time dependences of geomagnetic activity after passages of unstable filaments through centre of solar disc.

The question of the geoactivity of filaments, however, requires a more detailed investigation using not only statistical methods but also methods of analyzing the individual cases [72–77] which led to the need for the elaboration of the above classification of filaments. It was on the basis of such a classification that we could prove that there only seems to be disagreement in the conceptions of the geoactivity of filaments because the different types of filaments have different results, as is seen below:

Bound filaments: The geoactivity of these filaments was investigated by comparing the course of the geomagnetic activity with the CMP of the filament [6, 7]. It was clearly shown that there is no increase in geomagnetic activity after the CMP of filaments of this type.

Unstable filaments: When investigating the geoactivity of filaments of this type we used different methods, chosen in keeping with the character of the problem to be solved, and arrived at the following conclusions [7]:

When these filaments pass through the centre of the solar disc (or its immediate neighbourhood – max. a few degrees), a geomagnetic disturbance, usually a strong storm, occurs in 100% of the cases (Fig. 25). An increase in geomagnetic activity occurs even after the CMP of some non-central filaments oriented in the direction of the meridian (Fig. 26). The value of the time interval between the CMP or between the disappearance of a filament and the commencement of the storm varies between 27 and 53 hrs and it seems that it might depend on the degree of activity of the filament (Tab. VII).

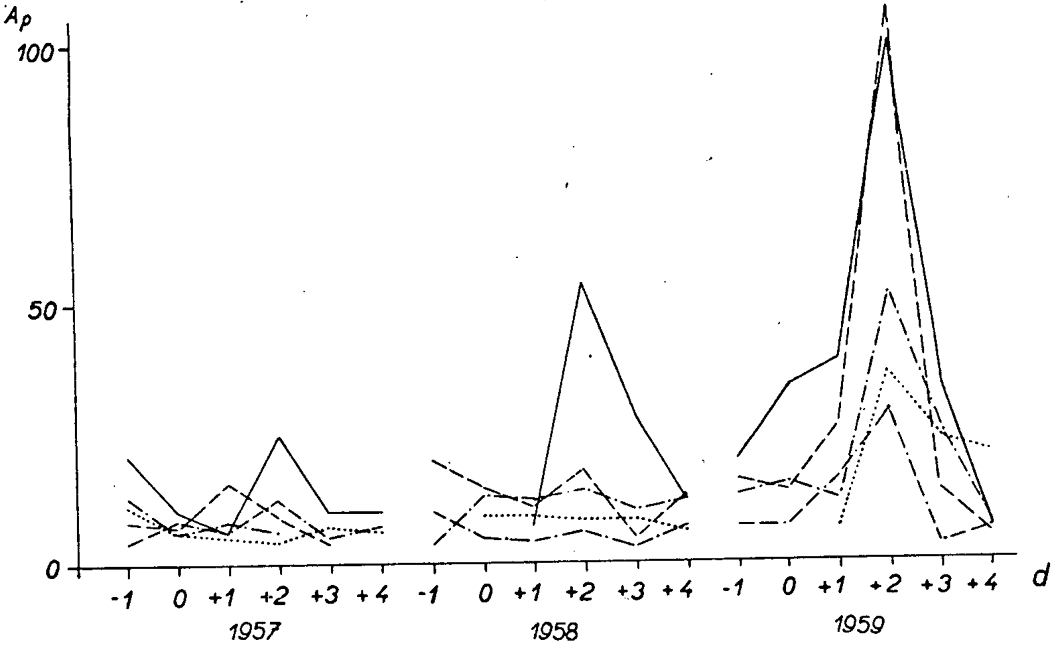

Fig. 26. Course of *Ap*-indices after CMP of non-central meridional filaments. The curves relate to the dates as follows: 1957: ..... 14. V.; — . — . 22. V.; — —. — — 27. VII.; — — — 8. VIII.; ——— 16. XI.; 1958: — — — 1. X.; — —. — — 9. X.; ..... 16. X.; ——— 2. XII.; — . — . 26. XII.; 1959: ..... 8.—9. II.; — —. — — 3. V.; — — — 10. V.; — . — . 22. V.; ——— 2. IX.

Free filaments: The indisputable geoactivity of filaments of this type was proved by an analysis of the different cases based on a comparison of the geomagnetic activity after the CMP of a filament in the periods before minimum solar activity [6]. It was found that as long as there is no local magnetic field between the free filament and the equator, then there is always an increase in geomagnetic activity after the CMP of the filament in a time interval comparable with the values for the unstable filaments [7]; thus the conception of the existence of corpuscular streams with very small velocity (interval of 4 or more days) is not confirmed [66, 78].

Here we give only the results valid for isolated filaments so that their geoactivity can be compared with that of other expressions of solar activity, discussed in the preceding paragraphs separately.

Table VII

*Mean values of time interval for different sets according to degree of activity*

| | Maximum degree of activity | | Medium degree of activity | | Lowest degree of activity | |
|---|---|---|---|---|---|---|
| | | No. of cases | | No. of cases | | No. of cases |
| time interval in hrs. | 28.3 ± 0.6 | 2 | 37.9 ± 0.9 | 11 | 50.9 ± 0.8 | 7 |
| velocity in km/sec | 1500 | | 1100 | | 800 | |

The results given here lead one to think that, due to the practically 100% connection between suitably placed unstable and free filaments and the geomagnetic activity, it is these that are the expression of solar activity which is the direct source of geomagnetically effective corpuscular radiation. However, further investigations [59] showed that the question of determining the direct source is not so simple; the whole matter becomes clearer if the connection with the solar corona is taken into consideration.

## The Corona and its Connection with Filaments

It is usually stated that the solar corona, changing markedly during the eleven-year cycle of solar activity, can be characterized by three basic types (Fig. 27):

a) The minimum type occurs usually in the period of the minimum of sunspots. It

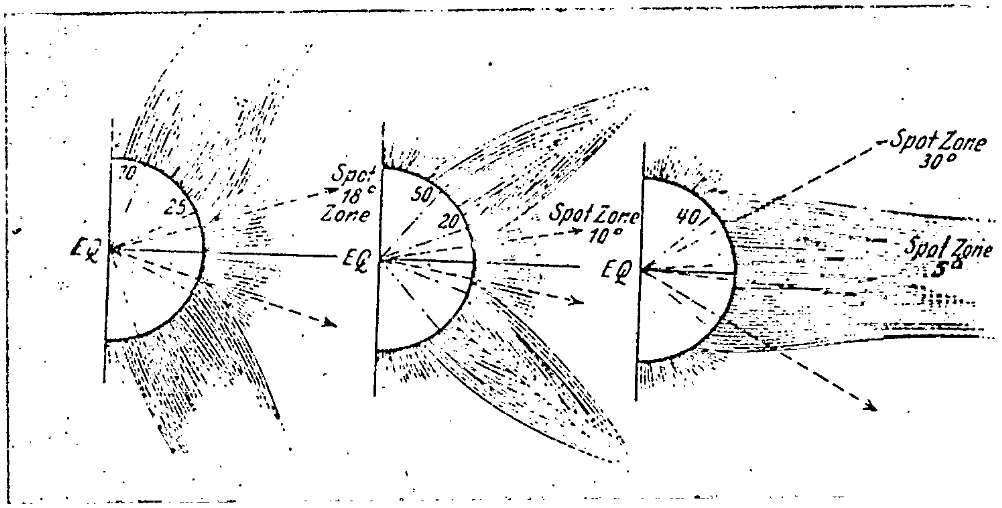

Fig. 27. Types of solar corona (maximum, intermediate, minimum) in relation to zones of prominences, marked by shorter radial lines (after [79]).

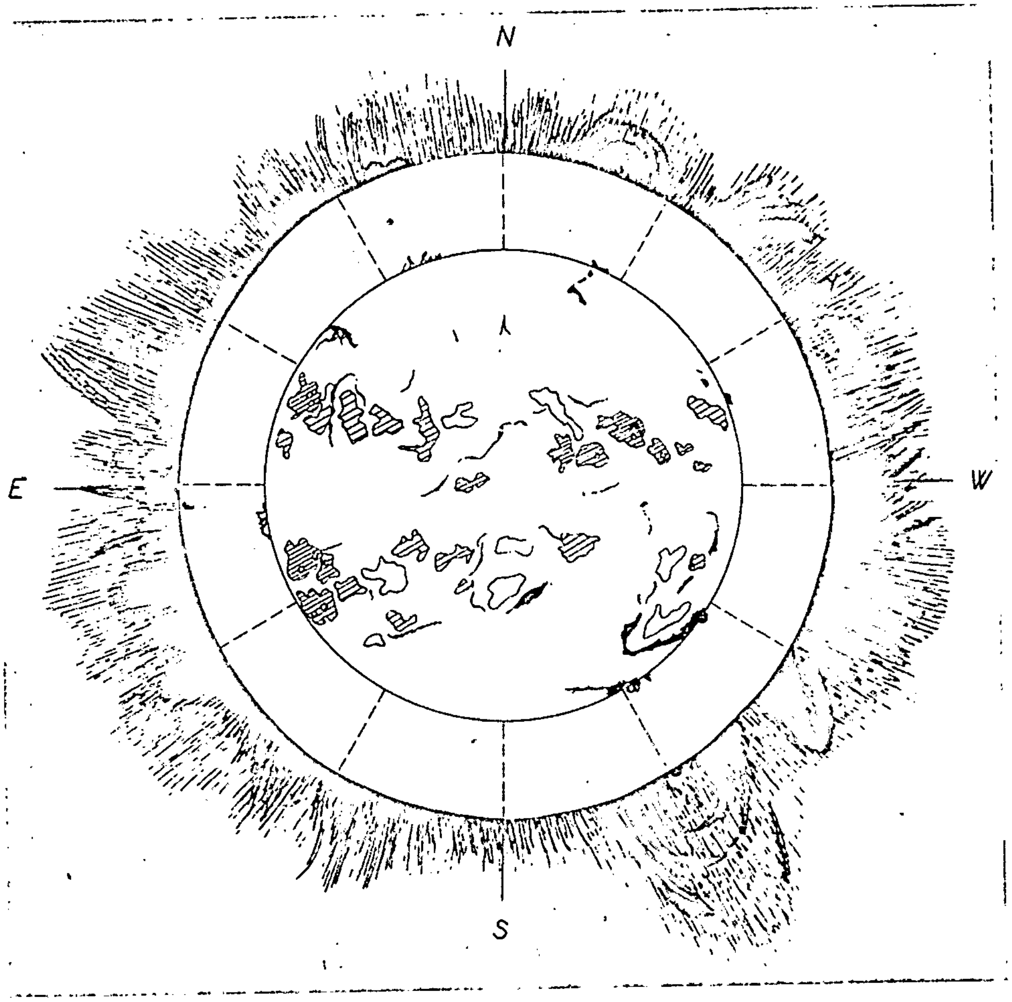

Fig 28. Comparison of structure of inner corona from 12. X. 1958 [80] with chromospheric situationaccording to solar map from Meudon. Since times of two observations do not exactly agree comparison is valid only for more permanent events.

is characterized by a particularly simple regular shape with long equatorial wings, without complex structures.

b) The intermediate type appearing in periods of medium solar activity is distinguished by a more complicated and less regular structure consisting usually of several coronal wings.

c) The maximum type, which is formed during high solar activity, usually has a very complicated ray-like shape with many coronal wings and streams.

The above types represent only the average idealized corona; in reality its instantaneous shape is given by the distribution of the different expressions of solar activity on the edge of the disc and thus also of the local magnetic fields. The best known and most pronounced is the connection between coronal formations and prominences. A certain coronal wing is sometimes regarded as a large three-dimensional copy of a filament which is in the base of this wing [1].

If we take into consideration the distribution of filaments (prominences) given above, we see their close connection with the shape of the corona. To bound prominences, as long as they occurred in the region of simpler local magnetic fields, one can ascribe the arched structure occurring in the base of the elongated elements – "helmets" – from the Sun (Fig. 28). When they occur in strong more complicated fields (sunspot groups) only arched formations are found. As regards unstable prominences, we found [7] that they correspond to coronal streams of cylindrical shape (Fig. 29) usually ascribed to facular fields [81].

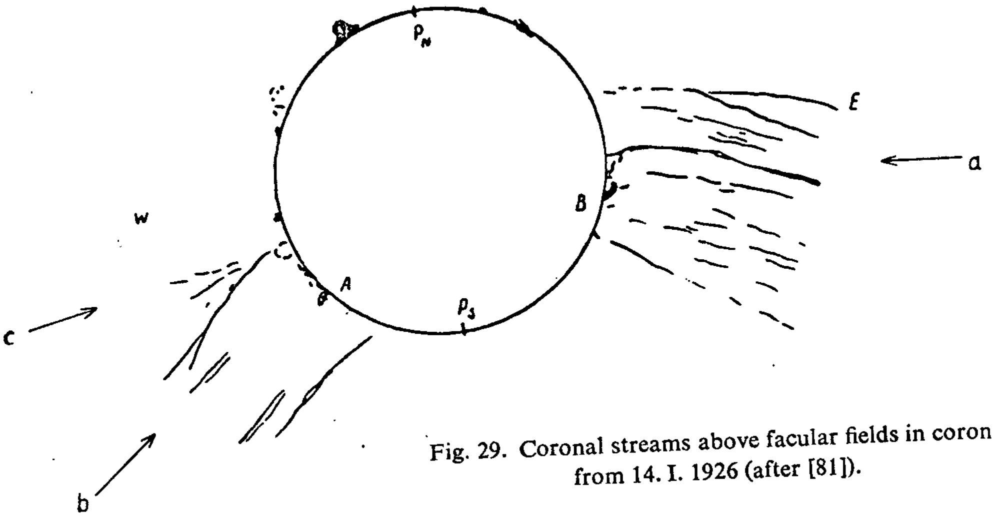

Fig. 29. Coronal streams above facular fields in corona from 14. I. 1926 (after [81]).

Free prominences are not seen in the corona above them by any corresponding formation.

We can now go on to explain the conditions for the emission of geomagnetically effective solar corpuscular radiation. The observed transformations of the bound (non-geoactive) filaments into the unstable type (geoactive) must obviously correspond to a change in the appropriate coronal formations above them. This, together with the minimum type of corona at free (also geoactive) filaments, permits the assumption that coronal formations represent the paths of corpuscular streams. The geoactivity of unstable filaments occurring on the centre of the solar disc, which has been proved quite definitely, is explained by a broad, favourably directed coronal stream rising above them, which in this case is pointed towards the Earth. The geoactivity of free filaments, which occurs if the filaments are high-latitude ones, can be explained by the concentration of the emitted corpuscles into the equatorial plane as a result of the effect of the total solar magnetic field, i.e. in the equatorial coronal wings which are aimed towards the Earth. In this way it was possible to explain the origin of geomagnetic disturbances which are ascribed to hypothetical *M*-regions [6, 82–84]. If a local magnetic field appears between the free filament and the equator (non-geoactive sunspot group), the arrangement of the minimum corona is disturbed and the corpuscular radiation is deflected from its original direction – negative effect of spots occurs.

It remains to explain that in some cases a geomagnetic storm occurs even during the passage of non-central unstable filaments through the central meridian [7].

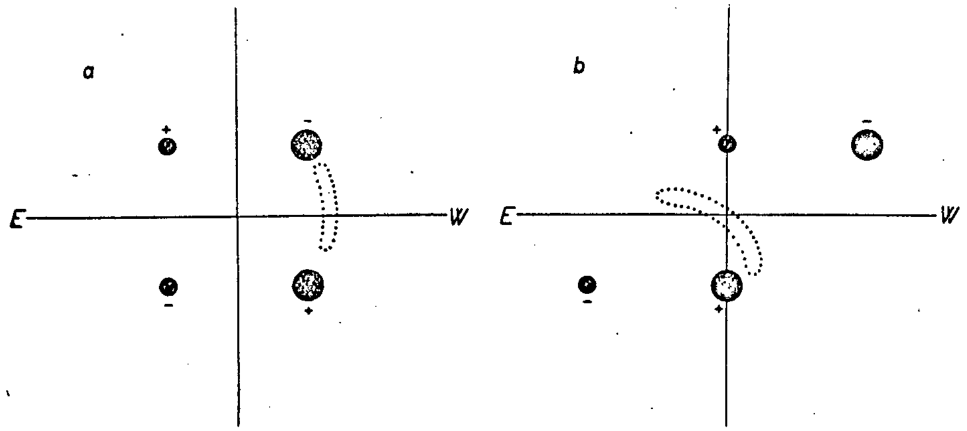

Fig. 30. Diagram of position of filament for different configuration of active regions.

It can be assumed that if the local magnetic field is temporarily compensated the corona may prematurely become the minimum type with equatorial wing pointing to the Earth and the emitted particles then move in the same way as in the case of free filaments. In this way one can obviously explain why there is no increase in geomagnetic activity after the CMP of active regions occurring symmetrically with respect to the equator but that after the passage of a pair of active regions somewhat displaced in heliographic longitude a magnetic disturbance sometimes occurs [85]. The explanation is obvious from the representation of the magnetic fields excited during simple configurations of idealized groups of spots [86]. It is seen from Fig. 30a that with a symmetrical arrangement of the sunspot groups the central filament, if it is formed, would be bound to the fields of both groups. In this case it is not very likely that there would be a synchronous change in both magnetic fields and, moreover, a change such as to cause the conversion of the filament into an unstable type. There is thus no reason for an increase in geomagnetic activity at such a configuration.

If, however, the arrangement shown in Fig. 30b occurs, then the central filament, if it occurs here, will try to take up a position along the boundary between the magnetic fields of the two groups of spots. In this case a change in magnetic field of only one group with which the filament is connected is sufficient for the transition to the unstable type; this gives rise to a favourable situation for the origin of a geomagnetic disturbance.

## 5) Deductions – On the Problem of Geomagnetic Storm Prognosis

The analysis made above mainly concerned individual solar phenomena from the point of view of their geoactive effects. It is quite obvious, however, that for a satisfactory explanation of the emission of corpuscular radiation, particularly in connection with the prognoses of geomagnetic storms, one cannot confine oneself only to separate investigations into the geoactivity of the above phenomena.

The conceptions on the role of the corona in the emission of corpuscular particles, discussed above, permit filaments to be regarded as indicators of coronal formations; this is of great importance in forecasting geomagnetic activity since the corona has not yet been continuously observed in its whole extent.

### On the Determination of the Direct Source of Corpuscular Streams

The question is, whether filaments contribute directly by their mass to the formation of corpuscular streams, as can be expected from the high percentage of cases when geomagnetic storms were preceded by filaments, or whether filaments merely determine the shape, position and change in the corresponding coronal formations which were themselves the source of corpuscular streams. If we take it that filaments are the source, then in the case of free filaments it should be possible to accept the conception according to which hydrogen masses escape from the filaments by diffusion into the surrounding corona [66], where they are quite ionized and the protons and electrons thereby released form the base of the corpuscular streams. This is also borne out by the slow weakening of the filaments which often lasts for several rotations. In the case of unstable filaments a larger amount of hydrogen atoms would get into the outer corona which, after ionization, would give rise to the possibility of the origin of important corpuscular streams.

### The Geoactivity of the Active Region as a Function of its Phase of Development

Let us first assume for the sake of simplicity that the active region is isolated. In order to understand the character of its geoactivity the duration of the active region is substantially divided into two periods: the first period is limited by the instants of the formation and decay of the facular fields and the second is given by the existence of a filament which was produced in the active region and outlasts the first period without disappearing. This latter period lasts from the decay of the facular fields up to the gradual decay of the filament.

As regards the geoactivity of the active region, two quite different cases may occur in the first period according to the instantaneous situation in the active region during CMP. If the conditions for the emission of a geomagnetically effective corpuscular stream, discussed in detail in the preceding paragraphs, are not satisfied a complete decrease in geomagnetic activity follows. In the opposite case a geomagnetic storm with sudden commencement occurs.

The geoactivity in the second period is clear as long as the region is isolated. After the CMP of the active region, which in this case reduces merely to a free filament, there follows a geomagnetic disturbance or storm with gradual commencement. This simple picture is of course complicated by the fact that not always only isolated active regions occur on the Sun. In the period around the maximum of solar activity, in particular, there is often a considerable concentration of different local magnetic fields in the immediate neighbourhood of the central meridian. It is therefore more difficult in periods of greater solar activity to determine in a simple way when a geomagnetic storm begins.

The negative effect of spots, causing the decay or temporary interruption of geomagnetic disturbances from the hypothetical *M*-regions, is the reason why these regions cannot be expressed otherwise than in the period of smaller solar activity, when there are less spots.

We proved of recurrent geomagnetic storms that they are produced by the joining up of several disturbances [82–84]. A disturbance with a sudden commencement, after the CMP of an active region through the centre of the solar disc, may be followed by disturbances with a gradual commencement after the CMP of high-latitude filaments.

## Prognoses of Geomagnetic Activity

On the basis of the above results, to which special solar observations contributed to a great degree [87, 88], it was possible to elaborate a method for the prognosis of geomagnetic activity*) and also on the basis of our own solar observations to start issuing test forecasts.

In prognoses one must distinguish the degree of reliability of the solar bases, since this is reflected in the varying degree of accuracy of the prognoses. The most exact are prognoses of the first kind on the basis of changes seen directly in the central solar meridian; this, of course, requires continuous detailed observation of the Sun for forecasting the time dependence of the geomagnetic activity (i.e. of all geomagnetic storms and smaller disturbances as well as geomagnetically quiet periods), which cannot be ensured at one station on the Earth. Such a prognosis can be given for a maximum of two days ahead. At sudden changes a 28–38 hr interval is commonly used, the length of which is made more exact according to the estimated degree of suddenness of the change in the solar situation. Prognoses of this kind should agree practically 100% with reality within the limits of accuracy of the interval used since here one is mainly determining a certain phenomen from a total of other phenomena on the basis of relations which in principle are known. High agreement of the

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*) This will be published in detail later.

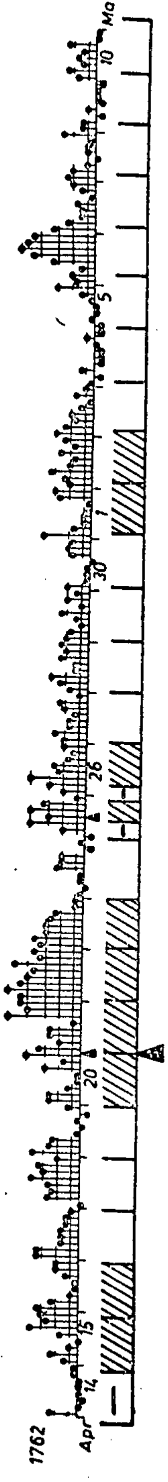

Fig. 31. Course of geomagnetic activity (top) and indication of prognoses of geomagnetic activity (bottom) from 14. IV.— 10. V. 1962. Hatched area — forecast of disturbance, horizontal line — forecast of quiet, triangle — forecast of ssc.

forecasts of the first kind with reality is actually observed in practice; of course, there are not many of them because data from continuous observation of the Sun are not available.

Prognoses of the 2nd kind differ from the first group in that the decisive changes were not observed directly but only the possibility of such changes was estimated from the character of the solar situation on the central solar meridian. The accuracy of prognoses of this kind, which are issued for the same period ahead and using the same time interval as for prognoses of the first type, is limited mainly by the degree of probability of extrapolating the development of the active region.

Less accurate are prognoses of the 3rd type, based on observations of the solar situation before the CMP, when extrapolation of the development of the active region must be made for a period of several days. These prognoses, which do not have to be made if data from continuous observation of the Sun are available, may be of greater importance only in periods of lower solar activity, when the starting point for prognoses are mainly long-term free filaments. In periods of greater solar activity they must be made as accurate as possible by prognoses at least of the 2nd type.

For illustration we give an example of a prognosis together with the course of geomagnetic activity for one 27-day period (Fig. 31). It is obvious that as long as solar observations were available, the prognoses could determine storms with a sudden commencement as well as several smaller disturbances and even the quiet periods.

Prognoses of geomagnetic activity based on the above principles, as long as our own solar observations were available, have been made since September 1959.

It is seen from the 135 prognoses issued so far that they agree with reality in 90% of the cases so that the above method can at present be regarded as very good; this is also borne out by the correctness of the conclusions based on our analysis of the connection between solar and geomagnetic activity.

## CONCLUSION

The problem of the origin of geomagnetic storms, as discussed here, represents a relatively very broad complex of problems which are solved in this connection. In addition to a general view of the partial phase of the general development of geomagnetic storms, our paper gives some new results of research, obtained recently, which contribute to the classification of storms and to clarifying the relations between geomagnetic and solar activity.

When classifying geomagnetic storms type analysis showed that the majority of storms has a two-phase course although one cannot neglect even that number of storms which exhibits a one-phase course. Such storms have a tendency to occur only in a certain period of the day.

A systematic investigation of the relations between solar and geomagnetic activity provided some important data contributing towards a decision on the causes of geomagnetic storms.

The relatively comprehensive material, on the basis of which the influence of sunspots on geomagnetic activity was determined, showed that the spots in themselves cannot be geoactive; a certain connection, found earlier in a number of papers, can be explained by the fact that other solar effects in the regions of spots were not taken into consideration.

An analysis of the results of observing flares, which was made in a number of papers both by statistical methods and for some individual cases, showed that flares might play a role in events which are followed by an increase in geomagnetic activity (in particular the occurrence of flares might disturb the shape of local magnetic fields on the Sun, if of course the flares themselves are not the consequence of the changes in these fields); it was found quite definitely, however, that flares are not the direct source of geomagnetically effective corpuscular radiation.

A study of filaments and the corona provided new results from the point of view of the causes of geoactivity. We made a new division of filaments into three groups and arrived at the conclusion that the filaments classified in unstable and free groups are very closely related to sources of geoactive radiation. However, it is not a simple problem to determine the direct source. It was found necessary to take into consideration phenomena occurring in the corona. An important role here is played by the approximately equatorial coronal streams or wings. The influence of the total magnetic field of the Sun is also very important in directing corpuscular radiation (particularly ejections connected with free high-latitude filaments).

The correctness of the conclusions we have derived is borne out by the reliability of the prognoses of geomagnetic activity based on our conceptions of the geoactivity of expressions of solar activity. The results obtained permit a unified interpretation of the connection between geomagnetic and solar activity throughout the solar cycle.

It is natural that it has not yet been possible to explain quite satisfactorily all the solar situations and the level of geomagnetic activity connected with them, on account of the very complicated conditions sometimes reigning on the Sun. A number of other problems will have to be clarified for such purposes, particularly as regards the local magnetic fields of the Sun.

The results obtained hitherto are mostly of a qualitative character, as followed from an elaboration of the results of observations and the correlation of geomagnetic and solar phenomena. This phase in research was indispensable for ensuring a sufficient base of new experimental grounds; it contributed towards the discovery of a series of new laws and should be continued. However, the problems have not yet been solved from the quantitative point of view as regards the investigation of physical conditions and the interpretation of the causes of the effects, as they actually occur, by the proposal of suitable theoretical models. These questions will be the subject of further work.

The discussion of events on the Sun shows that a decisive role in their formation is played by the magnetic fields, their distribution and dynamics. It is therefore important to explain their role in connection with geoactive processes and thus in relation to the origin of geomagnetic storms. In this respect it will be expedient to use inter alia the results of research into the internal geomagnetic field (particularly of continental geomagnetic anomalies and isoporic expressions) at present being done in our department [89] and at the same time to carry out model experimental investigations of the general magnetic fields with the possibility of applying the conclusions derived to the study of solar magnetic fields. From the theoretical point of view one must concentrate on the application of magnetohydrodynamical laws in explaining the causes of magnetic fields.

It is well known that the hydromagnetic processes taking place in the Earth's interior, which to a certain extent participate in the formation and maintenance of the Earth's magnetic field, have a relatively great similarity to processes on other cosmic bodies, i.e. on stars and thus also on the Sun [90, 91]. It is therefore expedient to make use of the results obtained from research into solar phenomena for the study of the Earth's magnetic field and vice versa. This procedure, common at many laboratories throughout the world where questions of research into the geomagnetic field are solved, is quite logical. This is because while relatively much is known about the geomagnetic field and its dynamic expressions (whether external or internal) we are not able to study directly hydrodynamic events appearing as the magnetic field on the Earth's surface. It is therefore indispensable that, apart from an analysis of the surface expressions of the geomagnetic field, analogies should be sought for the hydromagnetic processes in the Earth's interior and studied in those places where the mechanisms of such events, i.e. particularly on the Sun, can easily be investigated.

Quite analogously, research into the external geomagnetic field, the structure of which is observed at geomagnetic observatories, must use data from studies of processes, which are the source of the above disturbances or at least influence them to a certain extent, to explain the causes of geomagnetic disturbances.

Research work will have to be carried out along such lines both from the point of view of obtaining new experimental data and as regards theoretical generalization.

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Reviewer: **A. Zátopek**

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## Výtah

# K PROBLEMATICE VZNIKU GEOMAGNETICKÝCH BOUŘÍ

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Problematika vzniku geomagnetických bouří, jak je diskutována v předložené práci, představuje poměrně široký komplex úkolů, které jsou v této souvislosti řešeny. Kromě souhrnného pohledu na dílčí fáze celkového vývoje geomagnetických bouří jsou uvedeny některé nové výsledky výzkumu, námi dosažené za poslední období, které přispívají ke klasifikaci bouří a k objasnění vzájemných vztahů mezi geomagnetickou a sluneční aktivitou.

Při klasifikaci geomagnetických bouří typová analysa ukázala, že většina bouří má dvoufázový průběh, i když nelze zanedbat ani část, která ukazuje průběh jednofázový. U těchto bouří je patrná tendence výskytu pouze v určitém denním období.

Při systematickém vyšetřování vztahů mezi sluneční a geomagnetickou aktivitou byly získány některé důležité poznatky přispívající k rozhodnutí o příčinách vzniku geomagnetických bouří.

Poměrně rozsáhlý materiál, na jehož základě bylo provedeno posouzení vlivu slunečních skvrn na geomagnetickou aktivitu, ukázal, že skvrny samy o sobě nemohou být geoaktivní; určitou, některými pracemi dříve zjištěnou souvislost lze vysvětlit tím, že nebylo přihlíženo k výskytu dalších slunečních jevů v oblastech skvrn.

Rozbor výsledků pozorování erupcí, který jsme provedli v řadě prací jak statistickými metodami, tak pro některé jednotlivé případy, ukázal, že erupce by se mohly podílet na dějích, po nich může nastat zvýšení geomagnetické aktivity (zvláště tím, že výskyt erupcí by mohl narušovat a měnit tvar místních magnetických polí na Slunci, pokud ovšem samy erupce nejsou důsledkem změn těchto polí); bylo však námi zjištěno, že erupce nejsou přímým zdrojem geomagneticky účinného korpuskulárního záření.

Studium filamentů a korony přineslo některé nové výsledky z hlediska příčin geoaktivity. Provedli jsme nové rozdělení filamentů do tří skupin a došli k závěru, že filamenty zařazené do skupin nestabilních a volných mají velice blízký vztah ke zdrojům geoaktivního záření. Určení přímého zdroje však není jednoduchý problém; ukázala se nutnost přihlédnout k jevům, které nastávají v koroně. Důležitou roli zde hrají přibližně ekvatoreální koronální proudy nebo křídla. Velký význam při nasměrování korpuskulárního záření má též vliv celkového magnetického pole slunečního (zvláště při výronech souvisících s volnými filamenty vysokošířkovými).

Pro správnost závěrů, jež jsme odvodili, mluví spolehlivost prognos geomagnetické aktivity, založených na našich představách o geoaktivitě projevů sluneční činnosti.

Získané výsledky umožňují jednotný výklad souvislosti geomagnetické aktivity se sluneční činností v celém období slunečního cyklu.

Je přirozené, že zatím nebylo možno vysvětlit zcela uspokojivě všechny sluneční situace a s nimi souvisící stav geomagnetické aktivity vzhledem k velice složitým podmínkám, které někdy na Slunci panují. Pro tyto účely bude třeba vyjasnění ještě dalších otázek zvláště pokud jde o lokální magnetická pole sluneční.

Dosud získané výsledky jsou většinou kvalitativního charakteru, jak vyplynuly ze zpracování výsledků pozorování a z korelace geomagnetických a solárních jevů. Tato fáze naší výzkumné činnosti byla nezbytně nutná pro zajištění dostačující báze nových základních materiálů z pozorování, přispěla k objevení řady nových zakonitostí a je nutno v ní pokračovat. Uvedená problematika však dosud nebyla řešena po stránce kvantitativní, pokud jde o vyšetřování fysikálních podmínek a objasňování příčin zkoumaných jevů, jak ve skutečnosti probíhají, navržením vhodných teoretických modelů; tyto otázky budou předmětem další naší činnosti.

## Резюме

# К ПРОБЛЕМАТИКЕ ВОЗНИКНОВЕНИЯ ГЕОМАГНИТНЫХ БУРЬ

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Проблематика возникновения геомагнитных бурь в том виде, как она рассматривается в настоящей работе, представляет собой сравнительно широкий комплекс заданий, решаемых в этой связи. Помимо общей характеристики отдельных стадий всего развития геомагнитных бурь здесь приводятся некоторые новые результаты исследований, полученные нами в последнее время и способствующие созданию классификации бурь и объяснению взяимных связей между геомагнитной и солнечной активностями.

При классификации геомагнитных бурь типовой анализ показал, что большинство бурь имеет двухфазный ход изменений, хотя частью бурь, имеющий однофазный ход изменений тоже нельзя пренебречь. У таких бурь обнаруживается тенденция к появлению лишь в известное время суток.

При систематическом обследовании связей между солнечной и геомагнитной активностями были получены некоторые важные сведения, способствующие нахождению причин возникновения геомагнитных бурь.

Сравнительно обширный материал, на основании которого была проведена оценка влияния солнечных пятен на геомагнитную активность, показал, что пятна сами по себе не могут быть геоактивными; ранее установленную в некоторых работах определенную связь можно объяснить тем, что дальнейшие солнечные явления в областях пятен не учитывались.

Анализ результатов наблюдений вспышек, проведенный в ряде работ с помощью статистических методов, и анализ отдельных явлений показали, что вспышки могут принимать участие в процессах, после которых может иметь место повышение геомагнитной активности (в частности таким образом, что появление вспышек может нарушать и изменять форму местных магнитных полей на Солнце, но три условии, что вспышки сами не являются следствием изменения этих полей); однако мы однозначно установили, что вспышки не являются непосредственным источником геомагнитно эффективного корпускулярного излучения.

Изучение волокон и короны принесло некоторые новые результаты с точки зрения причин возникновения геоактивности. Было проведено новое подразделение волокон на три группы и сделан вывод, что волокна, отнесенные к свободным и неустойчивым группам, находятся в весьма тесной связи с источниками геоактивного излучения. Однако определение непосредственного источника не так уже просто; здесь обнаружилась необходимость учитывать явления, происходящие в короне. Важную роль притом играют примерно экваториальные корональные потоки или крылья. Большое значение для направленности корпускулярного излучения имеет также влияние общего магнитного поля на Солнце (в особенности при выбросах, связанных со свободными высокоширотными волокнами).

Правильность сделанных нами выводов подтверждается надежностью прогнозов геомагнитной активности, основанных на наших представлениях о геоактивности проявлений солнечной активности. Полученные результаты дают возможность однообразной интерпретации связи геомагнитной и солнечной активностей во всем периоде солнечного цикла.

Естественно, что пока еще не удалось вполне удовлетворительно объяснить все солнечные ситуации и с ними связанную геомагнитную активность из-за весьма сложных условий, создающихся иногда на Солнце. Для этих целей потребуется еще разрешить ряд дальнейших вопросов, в частности, что касается местных магнитных полей на Солнце.

Полученные до сего времени результаты имеют по большей мере качественный характер, так как они являются следствием обработки результатов наблюдений и корреляции геомагнитных и солнечных явлений. Такая стадия нашей исследовательской деятельности была необходима для обеспечения достаточной базы для новых основных материалов из наблюдений, так как она способствовала нахождению ряда новых закономерностей; поэтому такую работу следует продолжать. Однако приведенная выше проблематика не рассматривалась с количественной точки зрения, а именно, что касается исследования физических условий и объяснения причин возникновения исследуемых явлений так, как они протекают в действительности, а также проектирования пригодных теоретических моделей; этими вопросами мы будем заниматься в дальнейшей деятельности.