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# ORIGIN OF SOLAR WIND
# AND ITS ASTROPHYSICAL ASPECTS

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## ABSTRACT

This review paper discusses certain important problems pertinent to the origin of solar wind during the years of low solar activity.

The outflow of gases from places free of active regions is considered in section 1. Analysis of general structural properties of the solar corona, as shown in Figure 2, and of tinier structural details of the corona leads to the following conclusions:

a) the hypothesis concerning the general magnetic field of the Sun of dipole character is beset with a series of difficulties;

b) the gas outflow inside coronal streamers is apparently slower than the outflow of gases from other unperturbed regions of the Sun.

The problem of localization on the Sun of sources of quasistationary corpuscular streams (QSCS) is discussed in section 2. It is pointed out that the solution of this problem must take into account the subdivision of recurrent magnetic disturbances into two types: the usual R-disturbances and the classical M-disturbances (refer to Table 1).

The analysis of all available data performed in section 2, confirms the conclusions arrived at by the present author in [45, 46] that the main source of QSCS is in the optical-magnetic phase of active regions (refer to the model of such a stream in Figures 4 and 8). These streams induce the R-disturbances.

The discussion shows that the most probable source of M-disturbances, which are relatively scarce, is in QSCS originating mainly in the magnetic, trailing phase of active regions.

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The problem of linear dimensions of QSCS sources is discussed in section 3. Basing ourselves on the very long duration $\Delta T$ of numerous geomagnetic disturbances of the R- and M-types in periods of low solar activity, we reach the conclusion that the QSCS sources under consideration, which induce these disturbances, are located above the active regions within the solar corona, where they are considerably expanded in longitude and comparatively autonomous in their occurrence.

Besides, discussed also in section 3 is the question of origin of seasonal variations of geomagnetic activity. The conclusion is drawn that these fluctuations are the result of two factors: a) the approximate radiality of QSCS and b) the variation in the course of the year of the geomagnetic axis relative to the direction Sun - Earth.

Some problems of the origin of quasistationary gas outflow from the Sun are discussed in section 4. In a number of cases the presence of long-lived sequences of intense recurrent geomagnetic disturbances in the absence at that time of steady regions on the Sun with increased floccular and coronal intensity allows us to formulate a hypothesis, according to which certain, relatively stationary processes of nonthermal origin may take place within very expanded coronal regions, of which the center is located above the active regions. This conclusion is also corroborated by other facts dealt with in this paper.

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## INTRODUCTION

The problem of solar wind origin is a quite complex one. For its solution' every phase of the solar activity cycle must be discussed independently. We shall discuss in the present paper mostly the low level of solar activity.

It is quite important to stress at the outset that of all phases of the solar activity cycle (minimum, ascending branch, maximum, decsending branch) the most specific is the solar activity minimum. While the solar activity maximum characterizes the cycle mostly from its quantitative aspect (greatest number of active regions, sunspots, flares etc..), the cycle minimum constitutes a certain, very important and at the same time very complex transitional phase of solar activity development. Let us recall that the fundamental events enumerated hereafter, are observed precisely during solar activity minimum .

a) Substitution of the low-latitude belt of solar activity by the high-latitude one;
b) character variation takes place in the magnetic field polarity in sunspots of bipolar groups.

This complexity of the transitional period in solar activity development is also manifest in numerous other specific processes taking place in the Sun's atmosphere and, naturally, in its deepest layers at time of minimum and in its vicinity. One may think, for instance, that such peculiar phenomenon as corpuscular streams inducing classical M-disturbances, are precisely caused by the indicated processes.

Thus, while studying the gas outflow from the Sun during low solar activity, we must all the time bear in mind the singularities that this period characterizes.

For the sake of clarity of this exposé we shall consider various types of gas outflow from the Sun independently. Since mostly the period of low solar activity is under consideration, when sporadic geomagnetic disturbances induced by chromospheric flares are nearly absent, we shall forego the consideration of gas ejection from them.

Our aim in the present paper is not to provide a general expounding of the problem of gas outflow from Sun. For that we shall refer our reader to a series of specialized papers and reviews available in literature [1 - 8]. The main problem dealt with here is the discussion of the most debatable questions related to the ascertaining of the machanism of gas outflow from the Sun. For that reason, in particular, the latest results concerning the interplanetary plasma will be debated only to the extent of their relationship with the problem under discussion.

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## 1. SOLAR WIND FROM THE UNPERTURBED REGIONS OF THE SUN

According to contemporary representations, the main source of solar wind is the solar corona. The kinetic temperature of its lower layers (of about 1.5 million degrees as an average [9]) is so high that gases of the corona cannot be in the state of hydrodynamic equilibrium. To the contrary, the corona must be in a state of continuous expansion, and this process should be described by the hydrodynamic (or, to be more precise, magnetohydrodynamic) equations. The integration of these equations leads to the conclusion that the interplanetary space must be filled by hot plasma of coronal origin, continuously moving from the Sun in an approximately radial direction with supersonic velocities of the order of several hundred kilometers per second. From the mathematical viewpoint this problem has been the object of fullest treatment by Parker [2]. The methods and the results of the respective calculations, as well as the comparison of theory with observations has been already represented quite well in the earlier cited works, so that we shall not pause here upon them. As to the question whether some additional mechanisms (with the exception of the purely thermal), likely to create a sufficiently intense and comparatively stationary in time gas outflow from the Sun, are present, this question will be discussed in section 4 of this paper.

It is well known that the solar corona, studied particularly during total solar eclipses, reveals a very complex structure [10, 11, 12, 13]. That this structure plays a very great role in the problem of solar wind is beyond any doubt.Therefore, we must discuss in the first place the question of relationship between coronal structures (rays and others) and the magnetic fields of the photosphere.

The investigation of type-I comet tails (after F. Bredikhin [14]) and more particularly of comets observed at high ecliptical latitudes, shows that a sufficiently intense solar wind proceeds from the whole Sun and not only from low latitude regions. However, it is appropriate to consider separately: 1) the circumpolar regions of the Sun; 2) the remaining, comparativly low latitude regions.

1) Circumpolar Regions of the Sun

Photographs of the solar corona obtained at time of solar eclipses reveal in years of solar activity minimum well known polar rays, the so called "polar brushes". The specific form of polar rays has for a long time been considered as evidence of the presence at the Sun of a magnetic field of dipole character, with a dipole axis coinciding with the axis of rotation of the Sun. However, several difficulties arise in connection with this hypothesis:

a) The investigations by A. B. Severnyy [15], conducted by means of magnetographs with high angular resolution (5" - 10"), show at high latitudes that the magnetic field of the Sun is determined by a multitude of separate elements of different (!) polarity, intensity and length of the entire disk of the Sun, which began to be published in 1967 [16] (see Fig.1 obtained at the Crimean Astrophysical Observatory and the Mount-Wilson's magnetograms The latter are obtained with a smaller angular resolution of 23").

If we exclude from consideration the active regions, all such kind of charts do not usually indicate any prevalent direction of axis in the general magnetic field of the Sun.

Because of a simultaneous presence of areas with different polarity, the resulting field (mean field flux in the circumpolar region) may even be zero. Such was the case, for example, in the first part of 1964 at the Sun's south pole. In September-November 1965 the field was of identical polarity (southern) in both poles. A fairly clearly expressed magnetic asymmetry of the Sun in the sense of overbalance of Sun's magnetic field flux of one sign, and so forth was observed in isolated periods of 1964-1965 [15, 16].

b) The mean values of the field (a field, averaged by all longitude values is taken for each latitude) indicate a course of intensity with latitude which is distinct from the dipole field [15, 17]. In particular, there are no essential differences in the intensity of the general field at high latitudes and on low ones, provided in the latter case the field intensities are measured between the active regions.

The detailed study of polar coronal rays also raises a series of questions. Thus, according to [18], the divergence of polar rays with distance is greater than in a dipole field, whereupon the ray inclination may vary with the phase of the solar activity cycle. Besides, it is found in the detailed study by V. I. Ivanchuk [19] that polar rays are characterized by a rather different degree of expansion (widening) with distance, not only for various eclipses, but even within the bounds of a single corona's polar cap. In connection with this, conclusion was drawn in the works [19, 20] that the magnetic field of every polar ray is to a considerable degree "local" or autonomous, and that the source of such fields may be located not only in the sub-photospheric layers but in the corona itself.

Summing up the above considerations, we may indeed derive the conclusion that the hypothesis on the presence near the Sun of a general magnetic field of dipole character currently meets with a series of difficulties and that, apparently, polar coronal rays arise as a result of those complex processes that lead to the occurrence of the solar wind itself.

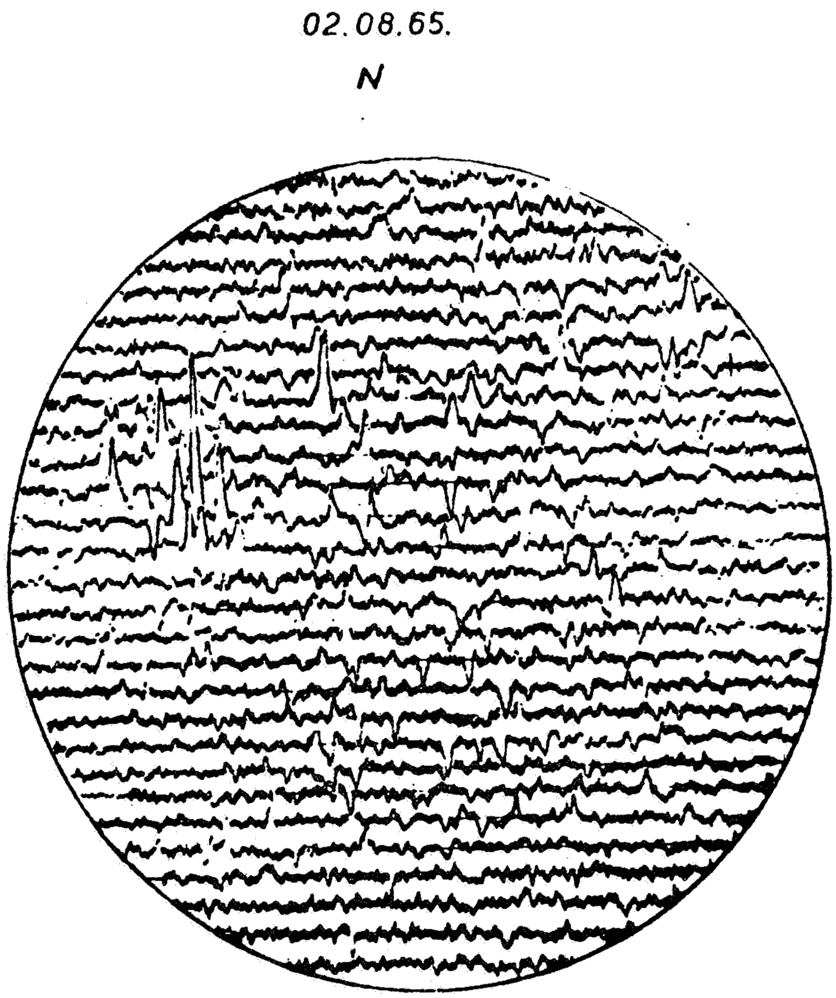


Fig.1

Chart of magnetic field distribution on the Sun obtained at the Crimean Astrophysical Observatory with high angular resolution

In connection with the above, the use of the dipole field for the study of the general structure of solar corona (as was done, for example, in [2],[21], calls for specific objections (see also the subsequent text). It is quite possible that at high latitudes the magnetic fields of the Sun are caused by migration toward these latitudes of the magnetic fields of active regions (ref. [22, 23]). However, this problem is obviously quite complex and requires further investigations. In connection with this, we should point to the work ref. [24], in which attempt has been made to show how the general magnetic field of the Sun can be constructed at the expense of turbulent motions of solar plasma and of Sun's rotation. (Note that the same can also be referred to stars).

## 2. Low-latitude Regions of the Sun

For further discussion we bring forth in Figure 2 the classification of coronal shapes as constructed by A. T. Nesmeyanovich and borrowed from [11], p.77. This classification is based upon careful analysis of a great number of eclipses and takes account of the most characteristic singularities of corona structure for various phases of solar activity. The "a" corona in Fig.2 corresponds to solar activity maximum, the "Д" corona is an ideally-minimum type of corona; related to this latter type are the 1934 and 1944 coronas. Note that the most characteristic properties of the general type of corona are determined by the latitude distribution of extended coronal rays in the near-solar space, that is, of streamers. In accord with the terminology introduced in [25, 26], we shall also refer to these rays as П -rays

In connection with Fig.2 there is another remark that we wish to make, which would attest about the absence on the Sun of a general magnetic field.

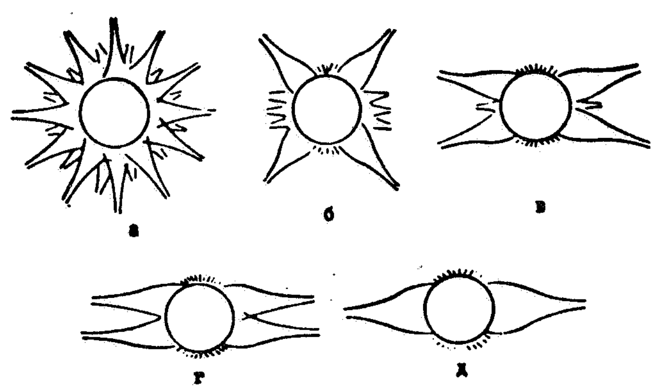

Fig.2

Classification of coronal shapes for various phases of solar activity after A. T. Nesmeyanovich [11]

Indeed, there is no relationship of any kind between the coronal structures of the southern and northern hemispheres (according to eclipse photographs) at low and middle latitudes. The coronal structures of opposite hemispheres behave more or less independently. This is illustrated in Figures 2В, 2Г by П-rays originating at middle latitudes. It is little probable that such rays, proceeding from the southern and northern hemispheres, may join somewhere at very great distances from the Sun.

The greatest interest is offered by the ideally-minimum type of corona, for here the influence of solar activity is minimum. As is shown in [27], a corona of the given type represents a system of a substantial number of fans, ending by rays stretched almost in the solar equatorial plane (!). Even at great distances from the Sun the rays in question proceed more or less parallelwise with respect to one another; at the same time no merging of any kind between neighboring rays is observed. This refers in particular to rays originating from opposite Sun's hemispheres (see the corona of the solar eclipse of 30 June 1954 mentioned in the Vsekhsvyatskiy's work [28]). Nor is there any link (on eclipse photographs) between the fine structure of the corona of northern and southern hemispheres.

The property of the ideally-minimum type coronas to locate themselves along the equatorial plane at great distances from the Sun means that maximum amount of coronal gases is concentrated in the solar equatorial plane. Assume now that these gases constitute a manifestation of solar wind. We should then expect that the Earth should hit the fluxes of the most dense plasma (from the ideally-minimum type of corona) at the moments of time when it is intersected by the plane of solar equator ($B = 0°$, June, December). Besides, one can hardly doubt that the general shape of П-rays (streamers) is to a significant extent determined by "frozen-in" magnetic fields [11]. Therefore, one should expect that at just indicated moments of time the Earth must hit the regions that are characterized not only by a relatively increased density of solar plasma, but also by increased intensity of the magnetic fields. However, the available data do not confirm this. Thus, for example, in the middle of 1954, when the ideally-minimum corona was observed, the geomagnetic activity has disclosed an opposite effect, that is, two weak equinoctial maxima, which corresponded to "residues" of sources of M-disturbances on the Sun [29]. Even judging from all measurements carried out during the last solar activity minimum with the aid of space probes, at the moments of time $B_0 \simeq 0°$ these probes failed to indicate any enhancement of either solar plasma fluxes or amplification of interplanetary magnetic fields!

It is true, however, that the absence of the indicated effects could possibly be explained by admitting that at great distances from the Sun the streamers expand so much, that the variation of heliographic latitude of the Earth in the range from 0 to $\pm 7.2°$ is too small for their detection. But this assumption is in contradiction with the findings of Pioneer-8's estimates that the diameter of separate interplanetary ray-tubes on the Earth's orbit is only 3 million kilometers [30]. At the same time the distance of the Earth from the equatorial plane at time of equinoxes ($B_0 \simeq \pm 7°$) is about 20 million km.

And, generally, a series of facts discussed in [25, 26, 1, 31, 32], convey the idea that, despite the great visible extension of П-rays, they do not "hold out" to distances comparable with the distance Sun-Earth, and even if they do so, it is in a considerably attenuated form.

In connection with this we should point to the work by Bohlin, Hansen & Newkirk [33], who studied the spatial structure of one large streamer with a base extending between the latitude 30 and 66°. The authors reach the conclusion that the distribution of velocities found from the "spiral" shape of the streamer bent by rotation, is in agreement with the conclusion of solar wind theory and is characterized by the following parameters: initial velocity $\lesssim$ 10 km/sec, and at the distance $r/R_{\odot}$ equal to 4.5, this velocity constitutes about 60 km/sec. However, without speaking of the still insufficient reliability of the respective observations, the indicated data are not in contradiction with the above, our own conclusion. Indeed, streamers are extremely stretched (extended) formations [25, 26] and only this already requires sufficiently high plasma velocities for their emergence and existence. (Refer to [1], p.228).

One should bring forth still another argument in favor of the idea that streams of the ideal-minimum type corona (and, by the same token, of close types) do not constitute an intense source of solar wind. Indeed, if, as this would follow from Fig.2 , the solar wind intensity inside the streamers were relatovely high, this would be manifest in the intensification of type-l tails at those moments of time, when these comets (at epochs of activity minimum) cross the solar equator. However, judging from all considerations, this is not observed. It is true that the statistical data compiled in [14] show that, apparently, in the region of lowest ecliptical and consequently heliographic latitudes, there is observed a certain "statistical" excess of comets with type-1 tail. However, this fact hardly refers to the problem u der dis cussion, for according to Fig.2, the equatorial corona concentrates in the solar equatorial plane only in the course of comparatively short time, precisely at the moment of solar activity minimum (Fig.2 ). At the same time, the statistical data discussed in [14] cover the whole solar cycle.

In connection with the above the question may be raised as to which regions of the Sun the solar wind originates from? Apparently, the answer would be as follows. The source of the solar wind is practically the entire area of the unperturbed Sun, including the regions occupied by the base of streamers. In this latter case the solar wind gases may pass between isolated elements of streamers' fine structure. One should bear in mind that such a structure is one of the most charcteristic properties of coronal streamers. Thus, the equatorial corona of the 30 June 1954 eclipse included, according to estimates of [27], up to 30 - 40 separate rays (at least within the structure of its lower parts, not including what we designate as interplanetary space). The absence of "continuity" in the structure of the solar corona, with the above reservation, that is, the presence in the latter of a notice able "porosity", is found from radioastronomical observations [34].

All this is equivalent to the hypothesis that solar corona consists of two basic components: the first (solar wind proper) is characterized by comparatively high plasma flow velocities, the second component (streamers) is characterized by comparatively low velocities.

Let us now consider briefly the question of relationship between the structure of the corona itself and its interplanetary extension. This question is still obscure. In its original work on the origin of magnetic field in interplanetary space, Parker [35] started from a structureless "continuous" corona (the fine structure was considered by him later [36]). This, in particular, was expressed in that the law of drop of magnetic field intensity was obtained by him by dividing the general flux of photospheric magnetic field by the quantity $4\pi R^2$ , where R is the distance of the given point from the center of the Sun. At the same time, there is basis to consider (see sections 2 and 4) that, for example, corpuscular streams originating from active regions are characterized by a rather well expressed filamentary structure. Is there such a filamentary structure also above the unperturbed regions of the Sun ? A specific answer to this question can not yet be given at present, and the only thing we can do is to bring forth here certain considerations. Firstly, the presence of more or less radial inhomogeneities in the Sun's supercorona observed above the entire Sun (and not only above the active regions) stems from radioastronomical observations (see [37 and 38]. However, whether or not these inhomogeneities are the sources of filamentary structure of solar wind at great distances is yet unclear, for the porosity in the observed "radio-astronomical" structure at large distances from the Sun is comparatively small. The question as to where isolated filaments, "coronal tubes" originated in the unperturbed Sun is also still unclear.

Certain conclusions could be drawn from the study of histograms of distribution of interplanetary field directions. Such histograms, constructed By Ness and Wilcox [39] for periods when the planetary geomagnetic index $K_p = 0$ and $K_p > 3$, are shown in Fig.3. The first case corresponds to the 'unperturbed solar plasma" and the second to the "perturbed" one. The most reliable histograms of Fig.3 (great number N of field direction determination) are obtained with the aid of IMP-3 (see lower part of Fig.3). These histograms show that the "spiral" character of the field (angle $\phi = 135°$ & $315°$, where $\phi = 180 - \alpha$ (see Fig.4) is present also in the unperturbed plasma. However, according to [35], this must take place in interplanetary plasma in the absence of filamentary structure also. This is why the question calls for further study. At the same time, it is interesting to note that the spiral structure of Fig.3 after the data of IMP-3 is significantly more clearly expressed for the case $K_p \geq 3$, than for $K_p = 0$. This is precisely what could have been expected from a series of geophysical regularities, particularly from the analysis of short-period oscillations of the Earth's magnetic field [5].

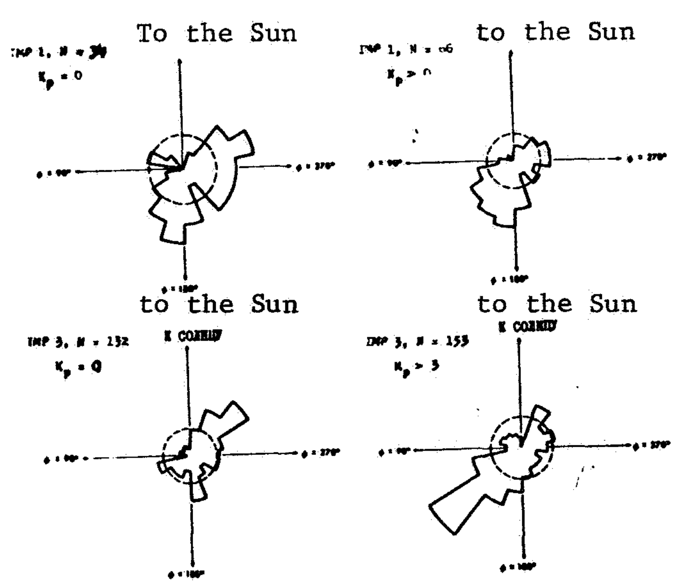


Fig.3

Histograms of distribution of intensity vector distribution of interplanetary magnetic field according to N. Ness and J. Wilcox [39] for various levels of geomagnetic activity

Let us make a small remark in connection with the mechanism of solar wind gases' outflow. One of the most important questions in this problem is the comparison of observed flow velocity of coronal gas with that given by the solar wind theory. Apparently, the most reliable is so far the method allowing us to judge about the velocities with which plasma moves in the corona, which is that of radar measurements of the Sun. One of the most complete such investigations was performed in [40]. Some of the results obtained in this work will be discussed briefly in section 4.

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## 2. PROBLEM OF LOCALIZATION ON THE SUN OF SOURCES OF QUASISTATIONARY CORPUSCULAR STREAMS

It is well known that numerous geophysical events (geomagnetic and ionospheric disturbances, polar aurorae and certain others) reveal a 27-day recurrence mainly on the descending branch of solar cycle and in the activity minimum. Conclusion was drawn accordingly that there are on the Sun certain sufficiently stable sources of corpuscular streams; we shall call these streams quasistationary (QSCS).

A large number of studies were devoted to attempts to localize on the surface of the Sun the sources of QSCS; however, the question remains open even at the present time. There are some causes for this uncertainty. We shall enumerate the main ones:

1) One of these sources of uncertainty was already pointed at earlier. It is the fact that the solar activity minimum is a transitional period of its development in time, which involves a whole series of singularities precisely inherent to the given period.

2) Discussing this problem, Bartels [41] reached as early as in 1932 the conclusion that at least in a certain number of cases the recurrent geomagnetic disturbances in the epoch of solar activity minimum can not be identified with the optical activity (flocculi, spots etc.) on the Sun. These isolated cases were generalized by Bartels, namely, he drew the conclusion that the source of all recurrent disturbances (and consequently of QSCS) are certain hypothetical M-regions on the Sun. However, from the standpoint of contemporary representations this generalization is not justified, for it is based upon data related only to solar activity minimum. Now we are aware that the history of every typical active region on the Sun (center of activity) can be subdivided into two phases: a) the first, optical-magnetic phase (o.m.phase), characterized by the presence in the active region of local magnetic fields and concomitant optical activity, and b) the second, the magnetic phase (m-phase), mainly characterized by the presence in the active region of weak local magnetic field. Here the optical activity is either absent or is quite weak. This second phase of active region existence may be called "magnetic tail" of the latter. Obviously, when defining in such a way the "active region", we have in mind that the second, magnetic phase of its existence is an entirely natural continuation (and then also the end) of the first phase.

Therefore, the absence of optical activity on the Sun still does not imply the absence on it of basic centers of solar activity development, i.e. of active region.

3) There are foundations [42] for subdividing the recurrent disturbances into two groups:

a) the standard recurrent disturbances observed in all phases of solar activity. The considered R-disturbances are observed also in the ascending phase of solar cycle. However, at that time the active regions are disposed at comparatively high heliographic latitudes and the revolution period of Sun's superficial layers around its axis is of about 28 days. This is why the recurrence of geomagnetic (and other) disturbances becomes sufficiently clear if we use the 28-day calendar of geophysical events; see on of such descriptive examples of such kind in [43]. The same considerations partially refer also to the maximum phase of solar activity.

b) The classical M-type recurrent disturbances, which we shall simply call M-disturbances. These are observed directly prior to and during the minimum epoch; they constitute only a small fraction of all recurrent disturbances. The clearest geomagnetic sequences of M-disturbances are described at length for the last five solar activity cycles in the work [42]. The differences between R- and M-disturbances are compiled in Table 1 of this paper.

As a matter of fact we should discount that there is nothing in common between R- and M-disturbances. Moreover, conclusion is drawn in the works [42 and 44] that the first terms of a number of M-sequences should rather be ascribed to R-disturbances. However, certain specific differences do exist between R- and M-disturbances (Table 1); they play an important part in the solution of the problem discussed in the present paper. At the same time, in the works so far completed on the problem of localization,no attempts of any sort are made to take into account the indicated differences, and this results in numerous uncertainties.

4) A very large number of investigations devoted to the problem of localization of sources of QSCS are based upon a comparatively limited material encompassing 1 to 2 solar activity cycles. This appears to be totally inadmissible, particularly in reference to M-disturbances. Indeed, each cycle of solar activity usually comprises quite a small number of M-disturbances. Consequently, the found relationships may be entirely casual; for more details on this, see [42].

Therefore, for the solution of the problem of location of QS sources on the Sun, we must: 1) take into account not only the optical-magnetic, but also the magnetic phase of existence of active regions; 2) study separately the R- and M-disturbances; 3) utilize for the analysis more prolonged time intervals (no less than 5 to 6 cycles).

Geomagnetic disturbances are most often used for the solution of the considered problem. However, we should bear in mind that the total pattern of geomagnetic disturbance is usually very complex; neighboring geomagnetic disturbances of same type are often superimposed to one another. Besides R- and M-disturbances, not always separable from one another, a specific role is played by sporadic disturbances of same or different types, caused by chromospheric flares, even in the year of low solar activity.. For that reason it is more correct and effective to proceed in the analysis starting from solar events, then linking them with the geomagnetic activity, rather than do it the opposite way.

At the present time there are all reasons to consider that the main role in the creations of QSCS is played by the active regions. Let us consider separately both phases of their existence.

TABLE 1

| Property of the disturbance | R-disturbances | Classic M-disturbances |
|---|---|---|
| 1 | 2 | 3 |
| 1. Most characteristic period of solar cycle, when disturbances are observed. | R-disturbances are observed in the course of the whole solar activity cycle. In the asecnding branch the recurrence period is close to 28 days. | M-disturbances are observed in activity minimum and during 2-3 years preceding it. |
| 2. Duration of the sequence of disturbances. | There is a broad spectrum in the values of sequence duration, from one revolution to numerous months. | M-sequences are characterized by normally high values of duration from 1.5 to possibly 2 years. |
| 3. Disturbance's link with source's optical activity on the Sun. | Link sufficiently clear, see Fig.5, though the oscillations of floccular and coronal intensity in active regions is notably greater than those of geomagnetic disturbances induced by the region. | Link quite uncertain. M-disturbances are often observed in practically total absence f steady optical activity on the disk within the limits of longitudes where corpuscle source can be located |
| 4. Duration of isolated disturbances inside a sequence. | Mean duration of a single R-disturbance is 3-5 days; it is noticeably greater only in years of low activity, ref. to Fig.9 | M-disturbances are often characterized by long duration ΔT, possibly attaining from 10 to 12 days. |

..continued..

T A B L E 1 (continuation)

| Property of the disturbance | R-disturbances | Classic M-disturbances |
|---|---|---|
| 1 | 2 | 3 |
| 5. Seasonal fluctuation of disturbances | On the average R-disturbances show seasonal fluctuations with two equinoctial maxima. | M-disturbances often show no seasonal fluctuations |
| 6. Intensity of the disturbance. | Quite notable a share of R-disturbances are characterized by weak intensity, though strong disturbances are observed | One of the most characteristic properties of M-disturbances is the fact that they are quite intense on the average; sequences of very strong disturbances are even at times observed. In any case, the energy included in one M-disturbance is, as an average, higher than the energy included in an R-disturbance. |
| 7. Presence of energetic particles in fluxes inducing the disturbances | This question is as yet unclear, though certain latest data [95] do point to the fact that in their optico-magnetic phase the active regions are also a source of energetic, but "soft" protons. | The available data attest to the presence inside certain fluxes, inducing the M-disturbances, of soft energetic protons (3-20 Mev) |

## A. Optically-magnetic Phase of the Active Region

The conclusion that in their optical (and, by the same token, simultaneously magnetic) phase, the active regions induce QSCS, was derived by the author of [45] in 1943. This conclusion was completed in 1960 [46] by the hypothesis that each quasistationary flux emerging from an active region is a combination of compartively stable in time and continuous in the entire "magnetic tube" length . The magnetic "tubes" are quite bent in space on account of Sun's rotation and low solar plasma velocities of 400 to 600 km/sec on the average. At the same time, at each point of such a flux, the plasma velocity vectors are approximately radial relative to the center of the Sun.

A model of such a flux, consisting of tubes, is represented in Figure 4 after [46] and [42]. The most contemporary expounding of the corresponding argumentation is given in [47], [42] and, partially in the review [1].

The statistical curves confirming the indicated conclusion and borrowed from [26] are shown in Figure 5. They are constructed on the basis of active regions in their optically-magnetic phase and carefully selected from the daily spectroheliograms of the Sun for the period 1907-1952, that is, for five cycles of solar activity (14 - 18). Only descending branches were used for the solar activity level when the prevailing disturbances are of recurrent type (S is the relative number of spots). The activity minimum itself is here excluded. In Fig.5, the time $\Delta t$ is plotted in days counted from the moment of time $\Delta t = 0$. of active region's passage in its o.m.-phase through the Sun's central meridian. For facility we shall abbreviate this denomination by PCM (passage of central meridian). The geomagnetic activity is plotted in ordinates. The dependence I is plotted for these active regions, which crossed the visible disk of the Sun at the PCM time), and the dependence II is constructed for those active regions (also in the o.m.-phase), which were distant, at time PCM by not less than 6° from the visible center. Fig.5 shows that the active regions, passing through the center of the solar disk, create in the phase $\Delta t \simeq + 6$ days of geomagnetic activity a clearly outlined maximum R. The same result is obtained for the descending branch of the last 19-th cycle [48]. At the same time, active regions of the group II induce no systematic fluctuations of the geomagnetic field. (The origin of these differences will be discussed in section 3).

Besides the maximum R, we find in Fig.5 still another, weaker maximum L and minimum $M_{in}$. The author of [49] has shown that these secondary details of statistical curves reflect only the longitudinal regularities in the distribution of active regions on the Sun. In particular, minimum $M_{in}$ is a natural "dip" between the main maximum R and its closest, most intense maximum L, created by the "preceding" active regions (that is, preceding with respect to those initial active regions according to which Fig.5 was plotted). (Refer to histograms of longitudinal distances in Figs 3-14 and Table 2 of ref.[49]).

A different interpretation of the maxima R, L and minimum $M_{in}$ is given in the Allen's work [50], and also in those by Parker and Roberts [51]. They advanced the hypothesis, according to which active regions create in the interplanetary space a certain comparatively empty cavity, "escape cone", while the outer boundaries ("surface") of this semi-infinite cone, with "summit" in the active region, are comparatively dense formations. The subsequent crossing by the Earth of the "escape cone", that is, of opposite "generatrices" of the cone located in the ecliptic plane, does precisely induce the maximum M at the outset, and then the minimum $M_{in}$ (in the given case a comparatively empty cavity) and, finally, the maximum R.

The following, exceptionally serious difficulty is indicated in [42] that concerns this hypothesis. Utilizing in Fig.5 the temporal distance (on Earth's orbit) between the opposite generatrices, escape cone "branches" (disposed in the ecliptic plane) creating the maxima R and L, and equal to about 6 days, one may compute that this corresponds to the linear distance along the Earth's orbit of about 200 million km. Further, the maxima R and L in Fig.5 are

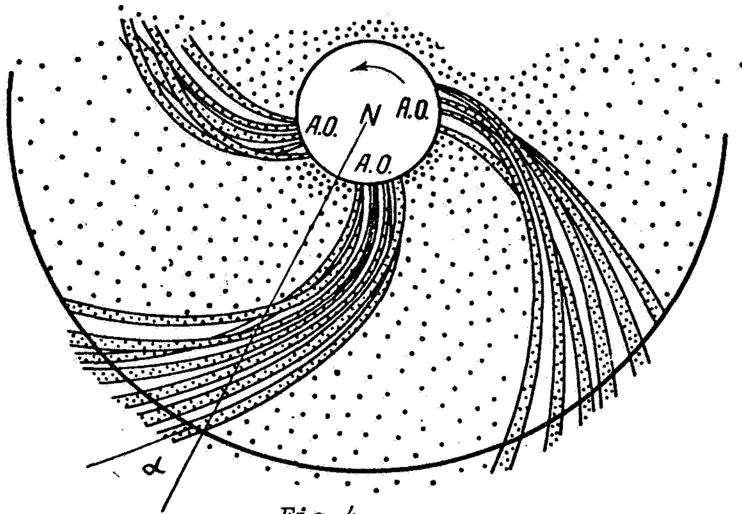


Fig.4

Model of corpuscular streams with magnetic tubes emerging from active regions, according to Mustel' [26]

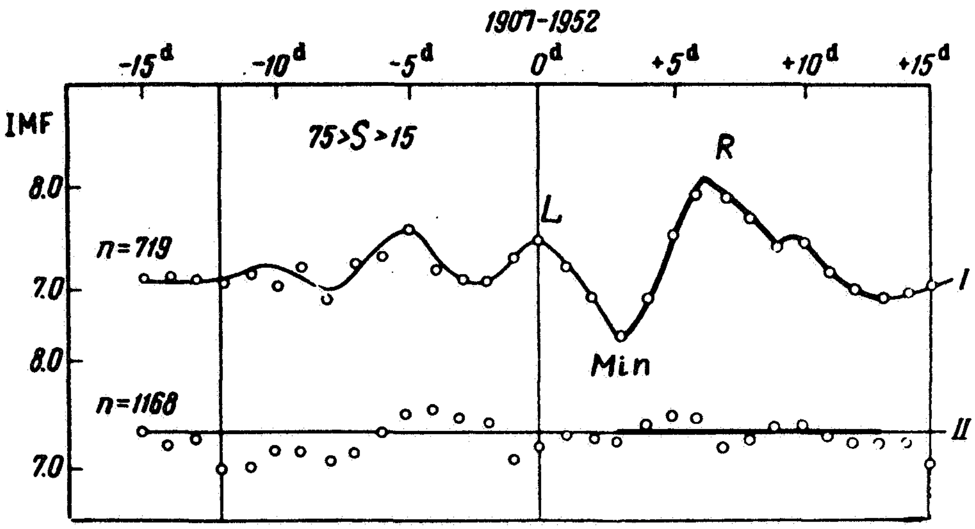


Fig.5

Curves of the method of superimposed epochs giving the course of magnetic activity with respect to the passage time of Sun's central meridian by group-1 and -2 active regions [26] characterized by a comparatively high geomagnetic activity and this corresponds [52] to corpuscle velocities of the order of 600 km/sec. Such solar corpuscles take less than 3 days to reach the Earth's orbit. On the other hand, the presence of the "escape cone" itself means that corpuscles, moving from a region adjacent to the active region, must have not only a radial but also a transverse velocity component. Calculations show that in order to "divide" for three days the branches R and L over 200 million km, gases in these branches must have a relative transverse velocity of the order of 800 km/sec. However, data on comet tails and those obtained with the aid of space probes [14], [53], show that on the average, the transverse velocity component of interplanetary plasma does not exceed 20 km/sec!

Another difficulty, indicated in [54], consists in the following. All initial active regions used for the construction of the statistical dependence I in Fig.5, may be subdivided into several groups as a function of the distance $\Delta L_C$ between the given initial active region and its closest preceding one (in the sense of PCM time). It is found that then the position of the maximum R in Fig.5 remains one and the same for all such groups, whereas the distance between the maxima R and L increases linearly with the rise of the quantity $\Delta L_C$ (see Fig.6, borrowed from [54]). Here plotted in ordinates is the position of the left hand maximum L, counted in days from the phase $\Delta t = 0$ days. Fig.6 shows that the position of the maximum L is determined only by the relative longitudinal of neighboring active regions! By the same token, the hypothesis on the escape cone loses all its sense, since for further increase of the quantity $\Delta L_C$ the maximum L vanishes, and a uniform background remains ahead of the maximum R, which is precisely observed when the number of geomagnetic disturbances is very small, A series of such cases are described in section 3, being borrowed from the work [47].

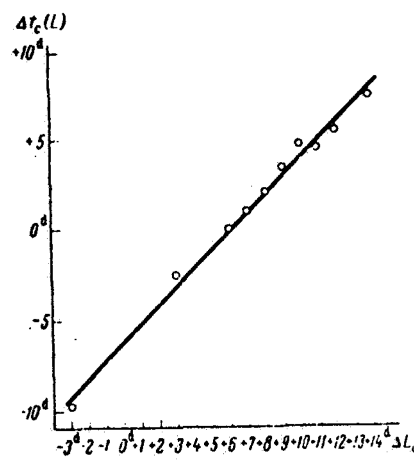


Fig.6

Position of the maximum L, preceding that of Fig.5, as a function of distance $\Delta L_C$ between the given, initial active region and its nearest preceding one [54]

Finally, in [47], section 3, other serious difficulties connected with "escape cone" hypothesis are summed up, whereupon considered also are the data obtained with the aid of space probes and analysis of solar cosmic rays.

Therefore, analysis of geomagnetic disturbances results in the conclusion that in their o.m.-phase, the active regions themselves are indeed the source of QSCS.

The conclusions derived are corroborated by the results of the following investigations:

a) Analysis completed by McCracken [55] has shown that solar energetic protons, ejected from chromospheric flares, which, as is well known, are always disposed inside the active regions in their o.m.-phase, propagate alongly strongly distorted trajectories originating in those active regions where the flare originated. (It should be borne in mind that flares are usually disposed in a region of noticeable local magnetic fields, and the latter do precisely play an important role in the creation of geomagnetic distirbances; (see the following point b). One can hardly doubt that these trajectories are determined precisely by those gases which constitute the QSCS emerging from the active regions and which carry alongside with them frozen-in magnetic fields of solar origin. The fact that the angle $\alpha_1$ between the total vector of the magnetic field and the radial direction to the given point on the Sun (see Fig.4), determined on the Earth's orbit from the study of cosmic rays (in this case this vector determined the propagation direction of cosmic rays from the Sun), practically coincides with the analogous angle $\alpha_2$ found directly from the variation of the total vector of the interplanetary magnetic field (see Fig.7, borrowed from the work [56]). This drawing has been constructed after the data obtained on 30 December 1965 with the aid of the space probe Pioneer-6. Both indicated angles $\alpha_1$ and $\alpha_2$ , on the average close to 45°, correspond approximately to measured velocities of interplanetary plasma . (Note that the case given in Fig.7 corresponds to that when the interplanetary magnetic "tube" are deformed by comparison with the "classical" spiral, see further).

Finally, these angles $\alpha_1$ and $\alpha_2$ coincide with the angle $\alpha_3$ which is shown in Fig.5 of the present paper, provided we take for the commencement of the disturbance the median art of the ascending branch of the maximum R, and convert the time $\Delta t \simeq +4.5$ days into the equivalent velocity ($V \simeq 450$ km/sec). Fig.5 is also based upon active regions in their o.m.-phase. In connection with this we should point out that the so called "magnetic bottles" play here no part of any kind, for they are formed by gases ejected from the active regions by the flare itself, and flowing along substantially less distorted trajectories (the high plasma velocities are of the order of 1000 km/sec).

The model corpuscular stream [46, 26], emerging from the active region, and consisting of combination of distorted and comparatively isolated magnetic tubes (see Fig.4), has been lately corroborated by Bartley, Bukata, McCracken and Rao [30]. Their investigations are based, as also is the work [55], on the analysis of cosmic rays moving from a chromospheric flare.

The new results obtained in [30] and in the adjacent work [56] are as follows:

a) in a series of cases the shape of magnetic tubes is distorted by comparison with the spiral (see the darkened curve in Fig.8 of the paper [56] and again the Fig.7 of the present paper). We should, in truth, point out that the relative dimensions of these deformations are comparatively small. With the view of improving the "descriptiveness" of the drawings, the deformations in Figures 7 and 8 have been strongly exagerated; b) The "thickness of the tubes" over the distance Sun-Earth has been estimated; it constitutes some 3 million kilometers (see [30]).

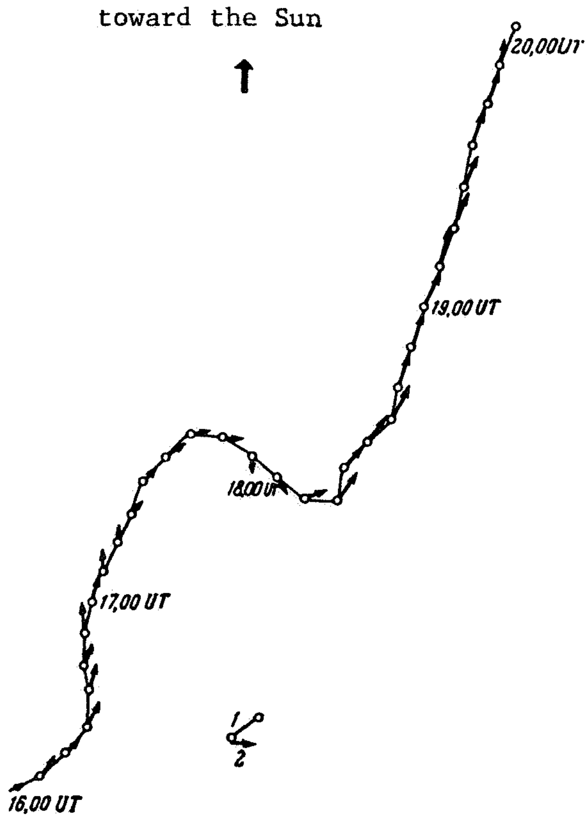


Fig.7

Direction, opposite to maximum cosmic ray flow from the Sun (arrows (2)) and direction of the interplanetary field vector (thin lines between successive circles (1)) projected on the ecliptic plane. The graph was constructed by McCracken and Ness [56] for 30 December 1965. The numerals give the Universal time.

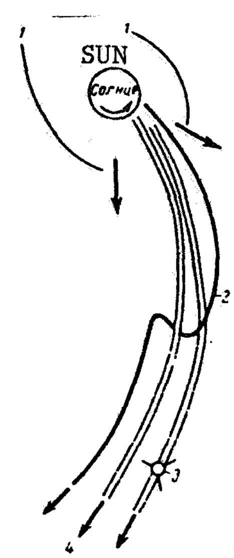


Fig.8

Model of magnetic tubes originating from the region of chromospheric flare (and by the same token from the active region), according to studies by Bartley et al [30]. In this drawing 1) is the solar wind; 2) is a deformed tube; 3) is the position of the satellite "Pioneer-6"; 4) is the direction of the magnetic field vector and of the cosmic rays' flux.

The same model of a corpuscular stream originating from an active region is also confirmed by the investigation of [57]. This investigation is linked with weak chromospheric flares, which may be studied particularly efficiently in the years of low solar activity. It is shown in [57] that energetic electrons, ejected from the chromospheric flares, propagate also along strongly distorted trajectories, originating without any doubt from active regions (i.e., where flares occur), that is, in their o.m-phase. Because of that, "magnetic bottles" cannot play any role here either.

Fig.3 is also evidence in favor of filamentary and spiral structure of fluxes emanating precisely from ac ive regions and inducing geomagnetic disturbances; this is particularly so in case of the probe IMP-3, for which a large number of data are available, considerably larger than for IMP-1. The histograms of Fig.3 show that the spiral structure is significantly better expressed for $K_p > 3$, that is, for fluxes inducing recurrent disturbances and not for the general flow of gases from the Sun ($K_p = 0$); see also [5];

b) the second important item, corroborating the hypothesis on active regions is the fact that, according to Wilcox,Schatten and Ness [58], the $K_p$-indexes are closely linked (by linear relation passing through the origin of coordinates where $K_p = 0$, $B = 0$) with interplanetary magnetic field intensity B, measured near the Earth, but outside the Earth's magnetosphere. This very fact already suggests that at time of geomagnetic disturbances, the Earth is situated in regions of solar plasma with increased values of B. At the same time, we are aware of the fact that spots with increased intensity of the magnetic field on the Sun, are precisely the active regions.

The results found in [58] and based upon the material obtained with the aid of space probe IMP-1, are corroborated in another work [59], based upon the data obtained on IMP-3. It is found that the indicated relation between $K_p$(or $A_p$)and the intensity B is dependent neither on the sectorial structure of interplanetary magnetic fields, nor on the phase of solar activity.

The fact that the values of $K_p$ are also linked with solar plasma velocities [60] is not in contradiction with the above considerations. Indeed, we are unaware, where areas are located precisely on the Sun, above which the solar plasma velocities attain highest values. The fact that the frozen-in magnetic fields and the velocities of solar plasma are distributed in the interplanetary space in a similar fashion (see magnetic sectors of interplanetary plasma in [61] and Fig.1 in the work [58]) is apparently only evidence that the highest plasma velocities are attained above the regions of the largest magnetic field.

## B. Magnetic Phase of the Active Region

The question of location on the Sun of sources of QSCS inducing classical M-disturbances, is significantly more complex. However, it may be said at the same time that nearly all the latest investigations link these sources with the last phase of active region existence, basically with the phase, when the increased optical emission in it is already quite weak or simply inexistent, while the main characteristic of the region is the local magnetic field. It is true that some of these investigations attempt to show that in their last phase, the active region induce generally all the recurrent disturbances (of the R and M types). Babcock [62] ventured the hypothesis in 1955 that generally the main source of all QSCS are the so called unipolar magnetic regions. However, in the work [63], the presence of such a universal relationship was not confirmed. And indeed, the material presented in the preceding sub-section A show that the sources of the bulk of recurrent disturbances are the active regions in their o.m.-phase.

The author of [44] expressed the hypothesis that the source of recurrent disturbances (mainly M-disturbances), which are observed without the presence of noticeable optical activity, are the active regions in their last magnetic phase. This assumption is corroborated by the following results:

a) a detailed review of all clearest, classical M-disturbance sequences of the last 5 cycles, completed in reference [42], has shown (as already mentioned previously) that in most cases the first terms of long sequences of M-disturbances are caused by active regions in their o.m.-phase;

b) it has been established in [61] and [64] by the autocorrelation method that there is a relationship between the magnetic fields on the Sun, the interplanetary magnetic fiedls and the recurrent geomagnetic disturbances. In these investigations, related mostly to the lower activity level, the weak magnetic fields on the Sun play a great role; they doubtless are the "tail" of active regions, earlier existing in their o.m.-phase;

The authors of the indicated works note that, besides anything else, an important role in the problem of localization and origin of QSCS may be played by the quasistationary sectorial structure of the interplanetary magnetic fields. However, the time period, studied in the works [61] and [64] is very small (see introductory remarks to section 2) and this is why the results obtained in these works require further corroboration;

c) in the solar activity minimum the recurrent disturbances connected with active regions in their o.m.-phase, and the classical M-disturbances have a common characteristic, which is the quite great duration of one disturbance, $\Delta t$, in both types )see section 3 of this paper).

## 3. DIMENSIONS OF THE SOURCES INDUCING QSCS

The question of dimensions (on the Sun's "surface") of sources inducing QSCS is important on account of a whole series of causes and, in the first place, on account of the following.

From the standpoint of conclusions, drawn in the preceding section, one could have anticipated that the dimensions of the source ought to coincide with the outer boundaries of the active region. However, the purely solar observations have not, so far, permitted to verify the above assertion, so that we are confronted with the necessity to involve the data that are related to great distances from the Sun. One might, for example, utilize the information obtained from the study of geomagnetic disturbances. The use of this information raises a series of questions that should be discussed.

### Extension of Sources in Longitude

The duration $\Delta t$ of a geomagnetic disturbance is determined in the first place by the extension C of a corpuscular stream, measured along the Earth's orbit. This extension C is in its turn determined by the following factors:

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a) longitudinal expanse $\delta L$ of the active region on the Sun; b) dispersion velocity of gases in the flow $\Delta V$; c) deflection of fluxes from radiality (*), these deviations are linked with the presence in moving gases of transverse velocity component $V_t$.

The longitudinal expanse of active regions in the o.m.-phase usually is of about one to two days. It may be further assumed [52] that on the average, the values of V on the descending branch of the cycle are comprised within the limits of 400 to 600 km/sec. At flow radiality, this gives a dispersion in time of about 1.4 days. Therefore, if it is expressed in days, C constitutes, at the expense of superimposition of both these factors, 2.5 to 3.5 days. As to the third factor, if we assume for $V_t$ values not exceeding, on the average, 20 km/sec, it can play no substantial role [14].

A rather large number of recurrent disturbances, free from the effect of mutual superimposition of neighboring disturbances, are indeed characterized by the values of $\Delta T$, comprised within the indicated limits of 2.5 to 3.5 days. However, the value of $\Delta T$ is greater in numerous cases. Particularly high values of $\Delta T$ are observed in the activity minimum itself. We present herewith the graph borrowed from [42] (Fig.9). This graph is analogous to the upper part of Fig.5. However, in Fig.9 the descending branch of solar activity cycles is divided in three parts in accordance with the limiting values for S, indicated on the left. The value of S is the smoothed value of the relative number of spots.

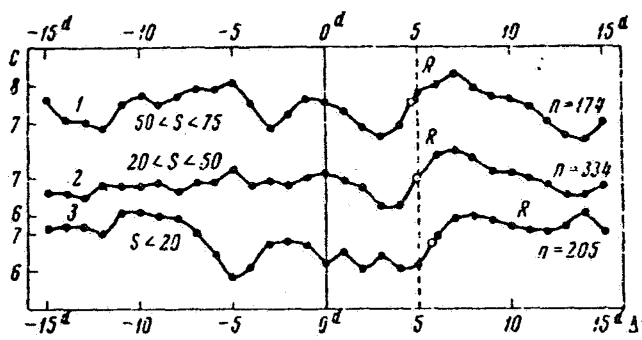


Fig.9

Curves of the superimposition of epoch method, analogous to the curve I of Fig.5, but constructed for various phases of the descending branch of solar activity. (S is the relative number of sunspots [42])

From Fig.9 we may see that the maximum of R for the two upper curves has practically an identical shape. At the same time, in the lower curve related to the activity minimum, the maximum of R has a "column-like" character; this means that here the mean duration of one disturbance is significantly longer. Note that all the three maxima of R in Fig.9 are somewhat widened along the abscissa axis (by comparison with the true duration of the disturbance), because the interval, that is, the lag $\Delta t$ between the PCM time for the active region and the commencement of the corresponding disturbance is somewhat different at the various active regions.

The indicated property of the values of $\Delta T$ is related to a still greater degree to disturbances that are part of classical M-sequences; at times the value of $\Delta T$ reaches up to 8 - 10 days (see, for example, [66] the well known sequence of classical M-disturbances of 1943-1944). In this regard, R- and M-disturbances in the activity minimum have analogous characteristics.

(*) the term "radiality", apparently inexistent in English expresses the radial state of the direction.

What is then the nature of such high values of $\Delta T$ in the activity minimum? The author of [44] linked the high values of $\Delta T$ in the activity minimum with the postulated very small values of solar plasma velocities (to 200 - 100 km/sec. The median part of the ascending curve of maximum in the lowest part of Fig.9 (clear circle) corresponds to a velocity of $\sim$ 300 km/sec. Identical values of velocities, of the order of 300 km/sec, follow also from solar plasma measurements carried out for the activity minimum (see Fig.3 from work [58]). In connection with this let us note that for a higher level of solar activity (for the descending branch of the cycle) the center of the ascending curve of R maximum in the uppermost part of Fig.9 and the measurements, carried out in [52] with the help of "Mariner-2" yield higher values of velocity for the periods of $K_p$ increase, from 400 to 500 km/sec.

From Fig.3 of [58] it follows also that the dispersion in plasma velocities is comparatively small, no more than 50 km/sec. All this does not allow us to utilize the explanation of great $\Delta T$, given in [44]. Nor is the introduction of transverse velocities $V_t$ to yield anything, for they are too low.

Moreover, if the corpuscular stream emanates from comparatively small regions on the Sun, its purely "geometrical" expansion on the path from the Sun to the Earth does not resolve the problem. Indeed, one should bear in mind that numerous M-disturbances have not only a long duration $\Delta T_M$, but also a simultaneous high, or even very high intensity $I_M$. In other words, numerous classical M-disturbances have the characteristic peculiarity, which is the high value of the <u>total energy</u> $E_M \simeq \Delta T_M I_M$ included in them!

The problem, arising in connection with the above, is quite complex, and this complexity is linked without doubt with specific properties of cycle minimum as transitional phase in the development of solar activity (see the Introduction to the present paper).

Taking the above considerations into account, it appears to be reasonable to attempt the explanation of the long duration of numerous type-R disturbances, and particulary of the type-M in the epoch of <u>activity minimum</u>, by the comparatively <u>large geometrical dimensions of the source</u> of flow inside solar corona above the active regions.(In the work [95] the solution of a like problem is based on a hypothesis that the magnetic field lines diverge from active regions in the shape of a peculiar, very wide "fan", occupying a large longitude range. However, this hypothesis (see Fig.11 of [95]) encounters from the standpoint of coronal observations, specific difficulties). At the same time, we must, however, have some representation of the reason why numerous M-disturbances are so intense. In [68] the origin of recurrent disturbances is linked with the phenomena of increased turbulence in flows of the considered type. However, it follows from the works [58] and [59] that the intensity of disturbances is to a great degree dependent on the intensity B of the magnetic field, frozen-in into the flow. On the other hand, this field in flows, inducing M-disturbances, is in no case greater than the field in the flows inducing the standard R-disturbances. This is suggested by the fact that local magnetic fields in the *o.m.*-phase are even greater than the field of active regions in their final phase. Therefore, it is possible that, contrary to conclusions of [68], the great role in flows inducing M-disturbances is much rather played by the <u>orderliness</u> of magnetic fields, and not the increased turbulence.

Let us now briefly examine what events on the Sun could constitute the link between the great expanse of sources of QSCS. It would be possible to admit that the stretched sources of flows may be "unipolar" regions [62], or the so called "activity complexes" [69]. However, this question is not entirely clear Indeed, in order to explain such geomagnetic sequences as, for example, that of 1943-1944 [66], it is necessary to admit that the corresponding source on the Sun has a longitudinal expanse up to 10 days (!), and it may then exist up to one year! Apparently, the "unipolar" regions and the "activity complexes" do not satisfy these requirements. Besides, as already mentioned, the lowermost curve in Fig.9, related to solar activity minimum and constructed for active regions in their o.m.-phase (of which a great number are very strong), also points to high values of $\Delta T$. At the same time, the expanse of the considered active regions is quite normal.

In connection with all the consideration in section 4 of the paper, the hypothesis will be considered, whereby the stretched sources of the considered flows are located in the corona and are characterized by a comparatively autonomous existence.

To conlcude the given question it should be remarked that there is still another hypothesis, brought forth by Mogilevskiy [70]. According to this hypothesis, even the "extreme" (or "edge") points of a prolonged recurrent disturbance are induced by central, most effective parts of the corpuscular stream. However, here too the question arises, why precisely M-disturbances are so prominent in their long duration.

## Extension of Sources in Latitude

Certain information on the expanse of sources of QSCS in latitude can be obtained from the study of geomagnetic disturbances. Thus, for example, assume that seasonal fluctuations in the number of recurrent disturbances are determined by the probability in the course of a year of the Earth hitting the radially-directed corpuscular streams from active regions. In this case, it may be concluded that the source of the corresponding flows does not "stretch" to the equator itself, but is approximately bounded by the low-latitude limit of the active zone on the Sun.

The question of origin of seasonal fluctuations in the course of geomagnetic disturbance has been discussed already in the course of numerous decades. Two hypotheses are proposed to explain these fluctuations:

a) according to the first, the so called axial hypothesis, seasonal fluctuations of geomagnetic activity are determined by the approximate radiality of QSCS and by the fact that near the equinoctial times (but not exactly at time of equinoxes) the radius-vector, traced from the Earth to the Sun, is located closest of all to zones of solar activity (when $B_0$ is maximum in its absolute value and close to 7°);

b) according to the second, the se called "equinoctial" hypothesis, the times of geomagnetic activity maximum are linked with those, in the given case equinoctial moments of time, when the angles between the geomagnetic axis and the normal to the direction of motion of corpuscles arriving from the Sun, assumes its least value. In the given case the character of solar corpuscular streams' interaction with the Earth's magnetosphere becomes essential.

In the review [1], the author brought forth a whole series of arguments in favor of the fact that over the descending branch of the solar cycle the "radiality" of QSCS plays a very great part in the problem under consideration. Over the ascending branch, during activity maximum and at time of the minimum itself, the radiality is manifest only to a feeble degree, if it is not altogether absent; this is particularly characteristic for the ascending branch of the cycle. However, there are a series of factors suggesting that the disposition of the geomagnetic axis relative to the direction of incoming corpuscles may play a definite role even over the descending branch. The author of [71] has shown, in particular, that for high-latitude geomagnetic stations the character of daily variations of geomagnetic activity is quite strongly dependent upon the season.

The conclusion that the "equinoctial" hypothesis is significantly better substantiated than the "axial" hypothesis was made by Wilcox in his review paper [8], where reference is made to the corresponding works on the subject matter in question. This is why we shall forego all the argumentations included in the work [8]. Note only, that according to Meyer [72] and Roosen [73], the seasonal maxima of geomagnetic activity coincide much more closely with the equinoctial times (23 September and 21 March) than with the moments of time when the quantity $|B_0|$ is maximum (7 September and 5 March).

At the same time there are facts which are evidence that in a series of cases the radiality of corpuscular streams still plays a <u>notable role</u> in the problem of seasonal fluctuations of geomagnetic activity. We shall enumerate some of them, whereupon we shall bear in mind mostly the <u>descending branch</u> of solar activity (see above):

a) Fig.5 is evidence of streams' radiality; contrary to the bulk of original data considered in the review [8]; it is indeed based upon a direct information on solar activity, and not on geophysical data. The days of active regions' passage through the central meridian of the Sun, utilized during the plotting of Fig.5, are represented for active regions of group I in the works [74] and [49], and for active regions of sub-group $II_u$ which refer to the so called "unfavorable" hemisphere [1], [26], in the work [75]. The active regions of the sub-group $II_u$ constitute the bulk of active regions of the group II and this is why the dependences of II and $II_u$ on the "MNE" (?) curves are nearly identical.

The utilization of lists of active regions, compiled in [74], [49], [75] shows that the seasonal distribution of the <u>number</u> of days of active regions' passage through the central meridian is practically identical for the active regions of groups I and $II_u$, which is simply linked with beforehand superimposed limitations, when sorting the corresponding active regions of both groups (on the descending branch of the cycle, most of active regions are disposed on low heliographic latitudes, and this is why at the times when $|B_0|$ is small, so is the number of active regions of both groups). In connection with this, the radical difference between the dependences I and II in Fig.5 MUST be fully ascribed to the fact that over the descending branch of the cycle, corpuscular streams are approximately radial, and for that reason, the fluxes emerging from active regions of the group $II_u$, by-pass the Earth! Note here also that the validity of the differences between the dependences I and II in Figure 5 is confirmed by statistical analysis [76].

b) In the years of low activity the mean heliographic latitude of active regions on the descending branch of the cycle is quite low, and this is why here, in the presence of radiality in the flows, seasonal variations of the geomagnetic activity must be quite noticeable. To the contrary, on the ascending branch of the cycle, the active regions are located at high latitudes and, for that reason, QSCS are "directed" toward the Earth comparatively seldom and, apparently in a casual fashion; and this is so because of "deflecting" factors. This is why the seasonal fluctuations on the ascending branch of the cycle must be substantially less expressed. This is fully confirmed by the Bartels' work [77], in which it is found that for the period preceding the cycle minimum, the amplitude $C_2$ of seasonal fluctuations is by a factor of 4 greater than $C_2$ for the ascending branch of the cycle.

c) The geomagnetic activity often attains quite high a level even in the neighborhood of solstices. It may be shown, for instance, that the long geomagnetic sequence of 1962-1963, of which the first term was clearly perceptible on 21 November 1962, revealed strong disturbances in the middle of December 1963. There are quite many such cases and all of them show that the orthogonality of the geomagnetic axis to the direction of motion of corpuscular streams can not hinder the onset of geomagnetic disturbances and cannot even noticeably weaken them! Note here also that the described cases of noticeable disturbances near solstices are naturally explained by deviation of streams from the radial direction.

d) The curves of geomagnetic activity, plotted by average monthly $A_p$-indices in the work [77], show a very feeble correlation with the relative number of sunspots. The "center of gravity" of the geomagnetic activity is shifted by a few years to the side of retardation toward the solar activity maximum. One can hardly doubt that this is linked with the radiality of corpuscular streams and with the increasing probability for the Earth of hitting the QSCS at transition from maximum to minimum of solar activity [71]. And we do know, indeed, that in the years of activity maximum, when there are present on the Sun an enormous number of active regions, periods with weak geomagnetic activity are comparatively easy to find; even their nearly total absence can be noticed.

e) To all the above expounded considerations we still may add the following argument. This consists of the fact that sporadic geomagnetic disturbances, caused by chromospheric flares, do not show any seasonal effects [50]. On the other hand, quasistationary streams and fluxes from chromospheric flares differ little from one another [71]. Consequently, had the geophysical event played a fundamental part in seasonal events of geomagnetic disturbances, they would have been manifest also for sporadic disturbances induced by chromospheric flares, which is not so.

How, therefore, should we connect the discrepancies between the conclusions drawn in [8] with the facts just discussed? We may point to two causes of such divergences:

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a) The main part of the investigations, upon which the discussion of the problem is based in [8], is related to the entire cycle of solar activity. At the same time, it was underscored above that the radiality of QSCS is sufficiently clearly manifest only on the descending branch of the cycle.

This is why the utilization of the entire cycle may diminish the anticipated effect of radiality to zero. Here a very important role must be played by very intense corpuscular fluxes from bright chromospheric flares, which exerted a strong influence on the conclusions derived in [8] only implicitely.

b) The second cause of the indicated divergences may be the fact that in the works, discussed in [8], the studied geomagnetic activity was that, whose level might, naturally, depend on purely geophysical factors (position of the geomagnetic axis in space and others). At the same time, the radiality of the flows must be analyzed in the first place from the standpoint of the NUMBER of corpuscular streams registered by the observer on Earth. Unfortunately, the evaluation of this number for various seasons is difficult, for the solution of the problem includes also the accounting of the just indicated geophysical factors.

Therefore, the investigations discussed in [8], which are essentially of geophysical nature, do not contradict the conclusions of [1] on the approximate radiality of QSCS, at least on the descending branch of solar cycle. Apparently, these streams are approximately radial in all phases of the cycle; however, their detection is easiest over the descending branch. To this we should still add the fact that the approximate ("on the average") radiality of QSCS follows also from measurements with the aid of space probes.

At the same time, we should again make the remark, that in a series of cases the indicated radiality is disrupted (apparently most often over the ascending branch of the cycle). Such disruptions, attaining up to 10°, are registered with the aid of space probes [78]. Here we may recall that, for example, the onset of recurrent geomagnetic disturbances on the ascending branch of the cycle (recurrence period of about 28 days) is most naturally explained by the fact [45] that during that time the fluxes, emerging from active regions, are in isolated cases deflected toward the equator, and, by the same token, they may be met with the Earth.

Returning to the main problem of the present section, namely that of the extent of sources of QSCS on the Sun, we may state the following. The fact that the number of recurrent disturbances reveals the seasonal fluctuations, is evidence that the sources of QSCS do indeed reach very often the Sun's equator and do not descend below the latitudinal boundary of active regions.

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## 4. PROBLEMS OF ORIGIN OF QUASISTATIONARY GAS OUTFLOW FROM THE SUN

### A. Corpuscular Streams from the Active Regions in Their First Optical and Magnetic Phase

Let us begin with the discussion of the question of solar corona structure above the active regions and of how this corona passes into the interplanetary space.

Above the active regions the solar corona is not homogenous and is characterized, in particular, by a series of peculiarities, of which the fine structure is the principal (see [10], [11], [12] and [13]. As far as we are concerned, the greatest interest resides quite naturally in the extended coronal rays, observed during eclipses. Related to them are: a) the relatively straight R-rays, discussed in detail in [25], [26] and [1], in Fig.15; see also [10], [11]); b) $\Pi$-rays, streamers (same references).

We should note here too, that $\Pi$-rays, streamers, are much rather characteristic of the last, mainly magnetic phase of development of active regions (if we judge by the presence of filaments on the Sun [79], and the discussion of Fig.10 in the section B of this chapter). Here we consider the first, o.m-phase; in particular, the results obtained in [55], [56], [57], [58] and represented in Figures 8 and 4, all refer precisely to this first phase of development of the active region, when chromospheric flares are observed in it. Besides, it is shown in section 1, that if $\Pi$-rays do reach the Earth's orbit, they do so in a very attenuated form. Therefore, here our interest must be centered mainly on R-rays.

As already pointed out in section 2, the study of QSCS leads to the conclusion [46], that each such stream constitutes a combination of very stretched magnetic tubes (see again Figures 8 and 4). Whether or not these magnetic tubes do constitute the direct extension of R-rays is still difficult to say though this hypothesis appears to be quite plausible. In any case, there can be no doubt that the tubes emerge from the solar corona. The linear thickness of R-rays at their base is of the order of 10000 km. If this thickness does not increase with the distance from the Sun as R, then on the Earth's orbit the thickness of the tubes must be of the order of one or several million kilometers, which is in accord with the estimate, made in particular in [30].

In connection with the problem of structure of corpuscular streams emerging from the active regions, we should point to Mogilevskiy hypothesis [70], [80]. According to this hypothesis, the stream consists of discrete plasma clouds with proper magnetic field (M-elements). These M-elements, moving radially from the Sun, are located along the isochrome, forming in their greater part a quasi-spiral system (Archimedes spiral) of magnetic lines of force. Contrary to earlier representations, the field of each of the elements is not linked with the Sun and has a complex structure.

The generation of the indicated M-plasmoids with proper magnetic field (from the stability condition such a field becomes comparatively rapidly force-free, were it not such prior to that) takes place continuously and relatively slowly, for a time approximately equal to $10^3$ sec. The generation process of plasmoids is linked with transfer from the photosphere (and from sub-photospheric layers) of relatively slow torsion oscillations which result in tube of force "overlashing" with the appearance of instability, and field annihilation in the region of the formed. From the energetic viewpoint such a process fully ensures a slow break-away of plasma with the field and may continue so long as the magnetic field exists in the active region.

E. I. Mogilevskiy considers that the latest investigations, completed with the aid of supermonitors [81], satisfy the model under consideration. According to these investigations there is observed in the interplanetary medium a chain of large-scale discrete magnetic fields ($10^{11}$ cm), reminding of the field of M-elements of the considered model. The latter explains also certain morphological peculiarities of geomagnetic disturbances, for example, the explanation of the existence of storm "families", see [82].

A very important problem of QSCS emerging from active regions is that of their interaction with the surrounding "unperturbed" corona, and at still greater distances from the Sun - with "unperturbed" solar wind. This interaction play an important role, because the velocities of the plasma moving from the corona above active regions are, as an average, greater than the velocities of an "unperturbed" coronal plasma. As a matter of fact this problem is still unresolved quantitatively. One may point only to the fact that the indicated interaction on the leading front of the stream proceeding from the active region, creates, starting from a certain altitude above the Sun, comparatively dense quasistationary regions [83], [1], [71], [47]. At the same time, shock waves may set in, which induce a SC on Earth even in recurrent geomagnetic disturbances [7], [84], [85]. The considerations, under discussion in [1], [71], [47], allow us apparently to grasp, why, for example, the angles of the spiral, for which $K_p \simeq 0$ and $K_p \geqslant 3$ in Fig.3 (particularly for IMP-3) are practically identical, though to these different values of $K_p$ respond different plasma velocities.

Up until now we considered the question of certain general and common properties of QSCS emerging from active regions in their o.m.-phase. What is the nature of the forces resulting in gas outflow from active regions? The most natural would appear to be the hypothesis, whereby the gas outflow is conditioned by processes of thermal dissipation even above the active regions. The available data are indeed much rather in favor of the idea that the kinetic temperature of gases in the corona above active regions is, on the average slightly higher (by about 500.000°) than above the unperturbed regions of the Sun (see for more detailed considerations the reference [13]). In connection with this, as was first noted by Krat [86], the active regions may be a particularly intense source of the solar wind. This hypothesis is also sustained by the presence of a positive correlation between the kinetic temperature of the interplanetary plasma and the magnitude of the rate of its recession from the Sun (see [87]. At the same time, one must bear in mind here the following circumstance stemming from direct comparisons of active regions (in their o.m.-phase) with the sequences of R-disturbances induced by them. These comparisons show that, inside any given sequence, the geomagnetic disturbances are much steadier than the optical floccular emission inside the corresponding active region. Thus, the optical floccular radiation inside a long-lived active region undergoes strong brightness fluctuations; at times it vanishes altogether, but the separate terms of the sequence induced by that region, maintain about the same intensity [88], [42]. In connection with this, one should note that the coronal radiation above an cative region follows rather closely the course of floccular emission. Here the shifts in time are comparatively small [89]. This is why the just indicated factors suggest that the temperature of coronal gases above an active region is possibly not the only factor determining the gas outflow from the region. This refers to a still greater degree to classical M-sequences (see further).

Thus, judging from every angle, the increased gas density above the active regions in their o.m.-phase do not play any great role in the origin of QSCS either (It was an earlier author's opinion that this fact does play an important role in the problem under consideration).

In truth there are foundations to consider that the corona has a normal density above the sources of corpuscular streams inducing classical M-disturbances (in fact approximately identical to that in the adjacent unperturbed regions). This follows from the fact that strong M-disturbances are observed often in the absence in the respective regions of the Sun of increased and, at the same time time steady floccular and coronal emissions, and also of increased radioemission (see [42] and the subsequent text).

All these complex problems of origin of QSCS will be discussed at further length in connection with the fluxes inducing classical M-disturbances.

## B. CORPUSCULAR STREAMS INDUCING CLASSICAL M-DISTURBANCES

The classical M-disturbances and the fluxes induced by them, constitute in the aggregate quite a peculiar phenomenon, mainly inherent to the 11-year cycle minimum and apparently linked with the complexity of the transitional period in the development of solar activity (see section 2 and also Table 1).

At that time exceptionally steady events are registered on Earth, such as quite long sequences of M-disturbances and comparatively short ones of R-disturbances, or even isolated disturbances of the same type (clearly of not a flare type).

One of the best characteristics of M-disturbances is the fact that they are often observed outside of any connection with the optical activity on the Sun, (see section 2 and the detailed discussion of [42] of the sharpest M-disturbances, beginning from 1920. This hinders extremely the localization of sources of the corresponding corpuscular streams on the Sun.

As was shown in section 2, one of the most probable variants in the problem of localization is the hypothesis that the source of WSCS are active regions in their last magnetic phase (see [44], [1], and, particularly [42]). In reality we have to admit that some unclear points still exist in this hypothesis. Thus, for example, it is shown in section 3 that the quite large width of the considered streams on the Earth's orbit (high values of the extent $\Delta T$ of M-disturbances) still remains unexplained. However, it was shown there too that the same takes place for the standard R-disturbances in the minimum (see the lowermost curve in Fig.9, plotted according to active regions in their o.m.-phase). This, in particular, generates the R- and M-disturbances!

Aside from the just indicated difficulty (and others also) the considered hypothesis is based, so far, upon quite limited and, at the same time, inhomogenous material on active regions in their magnetic phase. Thus, here a great amount of work is still imminent. However, at the same time, this hypothesis is currently the most plausible, and we shall make use of it as a starting point for the subsequent expounding.

We shall begin with the consideration of the structure of the corona at the base of corpuscular streams inducing M-disturbances. Obviously, here our information is quite limited. However, some of the points have to be noted.

The M-disturbances are observed in a whole series of cases in the absence on the Sun of any somewhat steady optical activity. At the same time, practically absent is also the slowly-varying Sun's radioemission component. Therefore, we may consider that the density of coronal gases at the base of the considered streams is nearly the same as in the adjacent, unperturbed corona.

As already pointed out above, the most characteristic coronal formations of the active regions in their last, magnetic, phase are the $\Pi$-rays, streamers (see again [79], and also Fig.1 of [1]). In connection with this a number of authors identify these streamers (i.e. their interplanetary extension) with the considered corpuscular streams (see, for example, [11], [33], [13], and also [96], where the presence of streamers is connected with the sectorial structure of interplanetary magnetic fields). A quite high stability of these streamers is noted in [33] and [13]. Newkirk [13] proposes the following sequence (A, B, C, D) of streamers' development, linked with the active region (see Fig.10, next page). The presently discussed streams should be linked with phases C, and, more particularly D of streamer development. It is considered that the streamer requires the presence of extended regions of opposite magnetic polarity (shown in Fig.10 in a schematic fashion for the phases C and D).

However, we have shown in section 1 a whole series of difficulties with which the corpuscular hypothesis of streamers is beset. Apparently, these difficulties are also taking place for the streamers connected with active regions. Let us point here to still another difficulty discussed at length in [25]. It follows from Fig.10 and from photographs of eclipses that, in their last phase, streamers have a very narrow ending (see phase D in Fig.10). This is in contradiction with the fact that, in a whole series of cases, M-disturbances do not reveal seasonal fluctuations linked with the variation of $B_0$. This means that in such cases the "latitudinal" extent of the streams is quite large. And, generally speaking, a whole series of facts discussed in [25] suggest that streamers, viewed as sources of QSCS of R and M-types can not induce seasonal fluctuations of geomagnetic activity. Finally, one may note still one more case speaking against the corpuscular hypothesis of coronal streamers. We have in mind the fact that the kinetic temperature of coronal gases at the base of the streamers is not higher (and possibly even lower) than the temperature of gases in the unperturbed regions of the solar corona, adjacent to the streamers.

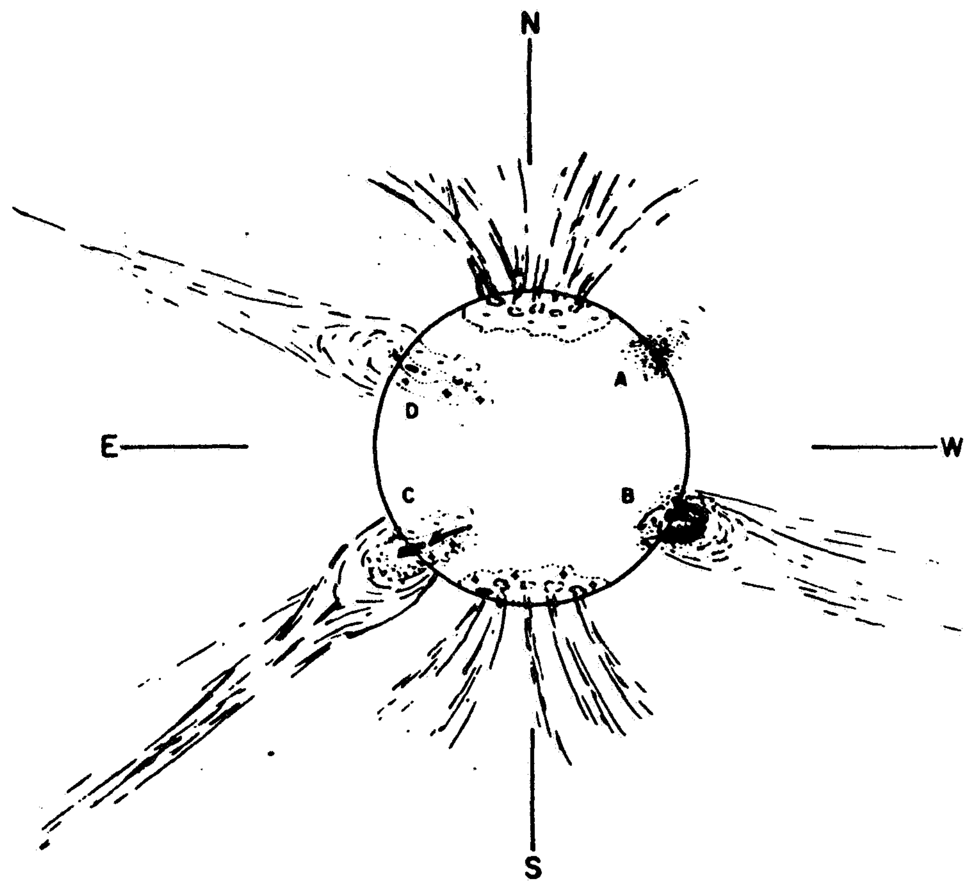


Fig.10

Model of the assumed evolution of a coronal ray (streamer), linked with the active region, after G.Newkirk [13]

Let us now consider the question of origin of corpuscular streams inducing M-disturbances. The absence in a number of cases of steady regions of optical activity (enhanced floccular and coronal emissions) that could be related to M-disturbances [42], is evidence that in the formation process of the considered corpuscular streams, the temperature characteristics of the sources of gas outflow do not play any substantial role, while, at the same time, numerous M-disturbances are characterized by a very high energy $E_M \simeq T_M \cdot I_M$ (see section 3).

What then is the mechanism creating the considered corpuscular streams? Apparently, here we are not in a position to speak of some "favorable" conditions of streams' exit from the Sun during activity minimum. Indeed, as a rule, standard and quite "normal" R-disturbances are observed also simultaneously with classical M-disturbances in the years of activity minimum. Further, in some cases, M-disturbances are also observed from 2 to 3 years prior to activity minimum (see the strong M-sequences of $D_i$ in [67]).

In connection with the above considerations, there is basis to examine the hypothesis [1] that at the foundation of QSCS, and particularly of those inducing M-disturbances, some processes of nonthermal character take place. Their role is still not quite clear, for here several possibilities are present: a) the processes may intensify the purely thermal gas outflow of the solar wind, corresponding to normal coronal temperature, which was considered in [2]; b) the processes may induce certain specific conditions inside the streams, usually formed by a standard thermal mechanism at normal temperature, which enhance the intensity of disturbances; c) the processes may themselves induce a sufficiently powerful outflow of corpuscles of various energies.

At the same time, as one may be induced to believe (see section 3), nonthermal processes must develop in sufficiently extended volume of the corona of which the center is located above the active region (see again the reference on page 22 of the current paper), but whose dimensions exceed those of the active region, even in its magnetic phase. Indeed, in this case we are in a position to explain in a natural way the origin of great values T of disturbance duration.

Following are the facts speaking in favor of the existence of the indicated quasistationary nonthermal processes in the corona, above the active region:

a) the presence of soft protons, with energies from 3 to 20 Mev, in corpuscular fluxes inducing recurrent magnetic disturbances [90]. The consideration of the respective graphs shows that the most intense proton fluxes are linked with the M-disturbances. A review of the latest research along these lines is given in [8]. A series of arguments are presented in [8] in favor of the fact that the acceleration of "soft" protons takes place not in interplanetary space, say, in the turbulent boundary layer between comparatively rapidly moving gases of the quasistationary stream and the usual gases of the "unperturbed" solar wind, but at the base of the corpuscular stream near the surface of the Sun;

b) According to [28], the intensity of frozen-in magnetic fields in the plasma and the solar wind velocities are distributed in space inside the sectorial structure of interplanetary plasma in an analogous fashion. This, apparently, is evidence that the plasma acquires its highest velocities on the Sun above regions of the greatest magnetic field. This immediately suggests the idea that we have to do with a certain acceleration mechanism, of which the very existence is linked with the presence of the magnetic field. It is true, however, that the intensity of floccular emission is linked with solar magnetic fields. Thus we should have admitted that here purely thermal processes of gas outflow take place. However, we have already indicated that the most intense M-disturbances are often observed in an almost total absence on the Sun of somewhat stable regions with increased coronal and floccular emission;

c) that the specific parts of the Sun, and, possibly, to a certain degree its entire surface, may constitute the place of development of some processes of nonthermal character, evidence is provided by investigation of X-ray and extreme ultraviolet radiations of the Sun [91], [92]. Namely, in a series of cases these investigations reveal the presence on the Sun of areas with intense radiation in the indicated spectral ranges, whereupon these areas show no notable emission of any kind in the optical range of the spectrum.

The facts enumerated here, as evidence of the presence inside the solar corona of certain, so far unknown, sources of particle acceleration, have a direct bearing on those representations about "solar corona autonomy", i. e., in the sense of photospheric processes' independence, to which we already referred in the section 3 of the present paper.

The following consideration also speaks in favor of autonomy representations (evidently with known limitations). Namely, that according to [64], [8], the sectorial structure of interplanetary magnetic fields is linked with the distribution of local magnetic fields on the Sun. However, the sectorial interplanetary structure reveals a notably greater longitudinal homogeneity in the distribution of fields of different signs (positive and negative polarity) than the structure of photospheric field distribution on the surface of the Sun. This is evidence of well known independence of processes in the photosphere and in the corona.

Therefore, the question of the possibility that certain quasistationary nonthermal processes take place inside the solar corona offers a great interest and must be studied by the most different methods, including the radar ones. In particular, the results of radar investigations of solar corona are presented in [40], while their possible interpretation, taking into account the regularities of the Raman effect, is given in [93]. Moreover, interest is aroused also by the question whether a comparatively quasistationary outflow of solar gases takes place also in the lower layers of solar photosphere. The discussion of certain data linked with the content of neutral hydrogen in interplanetary space, leads to the conclusion that such a possibility should not be excluded [94].

***** T H E  E N D *****

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