THE STRUCTURE OF THE SOLAR FLARE
STREAM MAGNETIC FIELD

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Abstract. The structure of the interplanetary magnetic field within the flare streams as well as associated variations of the geomagnetic disturbance are considered. It is shown that in the main body of the flare stream the magnetic field is determined by the configuration of the large scale magnetic field on the Sun at the flare region. Within the head part of the flare stream the magnetic field represents by itself the compressed field of the background solar wind and hence is determined by the distribution of the super large scale solar magnetic field outside the flare region.

A certain asymmetry in the parameters of the magnetic field within the streams associated with geoeffective and non-effective flares is shown to exist.

1. Introduction

The authors have recently shown (Pudovkin and Chertkov, 1976) the geoeffectivity of the solar flares to be determined by the sign of the meridional component of the large scale magnetic field on the Sun at the flare region. As the level of the geomagnetic activity is known to closely correlate with the sign and intensity of the interplanetary magnetic field (Fairfield and Cahill, 1966; Pudovkin et al., 1970; Arnoldy, 1971; Lanzerotti, 1968), the observed relation between the state of the geomagnetic field and orientation of the large scale solar magnetic field allows one to suppose the magnetic field ($B_f$) carried by the flare plasma to be also determined by the configuration of the magnetic field ($B_s$) at the Sun. However, this supposition was not confirmed experimentally for lack of the data on the interplanetary magnetic field. Now, when the necessary data are available (King, 1975), that supposition may be proved.

2. Experimental Data

There were chosen for the analysis 22 flares for which sufficiently thorough and regular information on the solar and interplanetary magnetic fields was available. According to the results by Pudovkin and Chertkov (1976), all the flares were separated onto two groups. One of those groups contained the flares which occurred in the regions where the meridional component of the large scale magnetic field on the Sun ($B_{sz}$) was directed southwards ($B_{sz} < 0$), and the second one contained the flares with $B_{sz} > 0$.

Figure 1 shows the characteristic variations of the interplanetary magnetic field (its scalar intensity $B$ and the value of the vertical component $B_z$) obtained by
Fig. 1. Variation of the parameters of the interplanetary magnetic field (B and $B_z$) and of the intensity of the geomagnetic disturbances ($AE$ and $D_{st}$-indices) associated with the flare stream passing; (a) for the flares with $B_{sz} < 0$, (b) for the flares with $B_{sz} > 0$, where $B_{sz}$ is the meridional component of the large scale magnetic field at the Sun at the flare region.

Averaging the data of twelve flares of the first group (Figure 1a) and of ten flares of the second group (Figure 1b) respectively. As the moment $t = 0$ there was chosen the moment (with the accuracy within 1 hr according to time resolution of the experimental data) of the shock wave passing, which was fixed onboard the satellite as an abrupt change of the intensity of the interplanetary magnetic field accompanied by the simultaneous increase of the DCF-field on the ground.

Besides, the figure shows the variations of the intensity of the geomagnetic disturbancies ($D_{st}$ and $AE$-indices) caused by the flare stream passing the Earth.

As is seen in the Figure, the characteristic behaviour of the interplanetary magnetic field allows one to distinguish in the flare stream two separate regions at least.
(a) \( t > 12-18 \text{ hr} \); this is a region with a relatively stable vertical component of the magnetic field \( B_{fz} < 0 \) (Figure 1a) or \( B_{fz} > 0 \) (Figure 1b). It is worth noting that the regions with negative values of the \( B_{fz} \) were observed in all the considered streams from the flares which took place in the regions with \( B_{sz} < 0 \). Similarly, all the streams associated with the flares occurred in the region with \( B_{sz} > 0 \) had the regions with positive values of \( B_{fz} \).

Thus the supposition on the relationship between the vertical component of the magnetic field within the flare streams and at the Sun seems to be confirmed by the direct satellite data.

(b) \( 0 < t < 12-18 \text{ hr} \). In this region intensity of the interplanetary magnetic field reaches the maximum. However the heights of those maxima are significantly different for the flares of the two groups under consideration (it is Dr L. Svalgaard who has pointed our attention to this fact). Indeed, in case when \( B_{sz} < 0 \) the magnetic field intensity increases from about \( 6 \gamma \) up to \( 15 \gamma \), and when \( B_{sz} > 0 \) it increases from approximately the same level of \( 6 \gamma \) only up to \( 9 \gamma \). What may be the cause of that difference in the behaviour of the magnetic field carried by the streams ejected by the flares of the two groups, is not clear as yet.

The vertical component of the interplanetary magnetic field is highly irregular in this region and does not seem to be associated with the field of the active region on the Sun.

According to the model by Hundhausen (1972), magnetic field within the leading part of the flare stream is in essence the compressed field of the background solar wind; consequently, the vertical component of that field is to be of the same sign as in the undisturbed solar wind just in front of the shock. However the data presented in Figure 1 do not allow one to come to such a conclusion. In particular, in Figure 1a the field \( B_{fz} \) in the region \( 0 < t < 12 \text{ hr} \) has the sign opposite to that within the undisturbed wind \(( t < 0 )\). In this connection we will investigate this problem more carefully.

In Figure 2a there are shown the variations of the interplanetary magnetic field as well as those of the intensity of the geomagnetic activity obtained by averaging the data for 5 flares of the first group \(( B_{sx} < 0 )\) which took place against the positive background (i.e. the vertical component of the magnetic field within the undisturbed solar wind \( B_{wx} \) was northward \(( B_{wx} > 0 )\) in those cases).

As one can see in the Figure, the streams under consideration are characterized by a significant compression of the magnetic field in their head part. The sign of the \( B_{fz} \) in that region coincides with the sign of \( B_{wx} \) within the undisturbed solar wind, and the value of \( B_{x} \) increases after the passing of the shock wave approximately in the same proportion as the intensity of the total field intensity \( B \).

Besides, one can see that the region with \( B_{fz} > 0 \) is followed by a region with stable negative values of the \( B_{fz} \) which may be identified with the main body of the flare stream. As we have already seen, the sign of \( B_{fz} \) in that region coincides with the sign of the meridional component of the large scale solar magnetic field and is determined by the distribution of the latter.
Fig. 2. The same as in Figure 1, for the flares with $B_{sz} < 0$ only; (a) against the positive background ($B_{wz} > 0$), (b) against the negative background ($B_{wz} < 0$), where $B_{wz}$ is the value of the vertical component of the interplanetary magnetic field within the undisturbed solar wind.

In Figure 2b the mean variation of $B$, $B_z$, $D_{st}$ and $AE$ is shown for the streams also associated with the flares of the first group; however in this case the streams occurred against the negative background (i.e. $B_{wz} < 0$). When comparing the Figures 2a and b, one can see the general features of the magnetic field behaviour to coincide in both cases. Indeed, in the both cases one can see significant
increase of the magnetic field intensity in the head parts of the streams as well as the existence of the region with stable negative values of the $B_{fz}$ within the main body of the streams. However in case when $B_{wz} < 0$ (Figure 2b), the intensity of the vertical component of the magnetic field within the region of the compressed solar wind does not increase and even may decrease so that the inclination of the magnetic field lines with respect to the ecliptics plane also decreases.

In Figure 3 there is shown the variation of the interplanetary magnetic field within the streams associated with the flares of the second group ($B_{sz} > 0$) against the positive ($B_{wz} > 0$) or negative ($B_{wz} < 0$) background (Figure 3a and b respectively). One can see from the Figure that the structure of the magnetic field in this case is in general similar to that in the previous case. Indeed, one can observe within the stream a region with positive values of the vertical component of the magnetic field ($B_{fz} > 0$) which seems to correspond to the main body of the flare stream, as well as the region of the compressed solar wind. However, as we have

Fig. 3. The same as in Figure 2, for the flares with $B_{sz} > 0$ only; (a) against the positive background ($B_{wz} > 0$), (b) against the negative background ($B_{wz} < 0$).
already noticed, the whole picture seems to be in this case more smoothed and vague.

When considering the streams against the positive and negative background separately, one can see that in case when $B_{sz} > 0$ and $B_{wz} < 0$ (Figure 3b) which is analogous to case when $B_{sz} < 0$ and $B_{wz} > 0$ (Figure 2a), the vertical component of the interplanetary magnetic field within the region of the compressed solar wind has the same sign as $B_{wz}$ in front of the shock and increases with respect to that. Similarly, the behaviour of the interplanetary magnetic field in case when $B_{sz} > 0$, $B_{wz} < 0$ (Figure 3a) is analogous to that in case when $B_{sz} < 0$, $B_{wz} < 0$ (Figure 2b), and the value of the $B_z$ in the region of the compressed solar wind is less that just in front of the shock. Thus, the noted above dependence of the parameters of the magnetic field of the stream on the orientation of that field with respect to the field in the background solar wind seems to exist in this case too, although the physical nature of that dependence is not understood.

Concerning the magnetic field frozen in the main body of the flare stream, the data presented above seem to confirm the idea by Pudovkin and Chertkov (1971; 1976) according to which this field is determined by the distribution of the large scale magnetic field at the Sun's surface. An additional confirmation of that supposition is given in Figure 4, where the value of the vertical component of the interplanetary magnetic field $\langle B_z \rangle$ is given in dependence on the flux $\phi_z$ of the meridional component of the large scale magnetic field on the Sun. In this Figure $\langle B_z \rangle$ is the mean value of $B_z$ obtained by averaging the $B_z$ (King, 1975) over 24 hr beginning from the moment in $2(1+\frac{1}{2}\sin |\lambda|)$ days after the flare and $\lambda$ is the geolographic longitude of the flare.

The values of $\phi_z$ were calculated in the same manner as by Pudovkin and Chertkov (1976): a circle with the radius corresponding to 100 000 km at the Sun and with the centre at the centre of the flare was drawn on the map of the Sun. Then that circle was divided into two parts by the diameter parallel to the ecliptic plane, and the fluxes of the magnetic field emerging from the two half-circles were calculated and their algebraic half-difference was taken as a measure of the flux of the meridional component of the magnetic field closed above the flare.

In contrast to the previous analysis it was not necessary for this study to have the continuous data on the interplanetary magnetic field for the whole three days; so we could investigate in such a way about 60 flares.

It is evident from Figure 4 that the values of $\langle B_z \rangle$ and $\phi_z$ are connected sufficiently closely (correlation coefficient $r = 0.55$), which enables one to predict the mean value of the vertical component of the interplanetary magnetic field and hence the mean level of geomagnetic activity on account of observations of the solar magnetic fields.

In Figure 5 there are shown analogous data for the azimuthal component of the interplanetary magnetic field. As is seen, dispersion of the experimental data is in this case significantly larger than in Figure 4. This may be explained by the fact that the azimuthal component of the interplanetary magnetic field is determined
Fig. 4. The daily mean values of the vertical component \( \langle B_z \rangle \) of the solar wind magnetic field in dependence of the flux of the meridional component of the solar large scale magnetic field \( \phi_2 \). Solid circles correspond to the central flares (\( |\lambda| < 45^\circ \)), open circles to non-central flares (\( |\lambda| > 45^\circ \)); the triangles correspond to flares that appeared in regions with extremely complicated structure of the magnetic field, and the squares show two flares that occurred on the same day in different regions. The thin bars show the probable errors.

not only by the azimuthal component of the solar magnetic field but also by the radial component of the latter due to the spiral configuration of the solar wind magnetic field lines. Nevertheless the data presented in Figure 5 show the same trend for the \( \langle B_y \rangle \) to depend on the value of \( \phi_\lambda \) (\( r = 0.3 \)). The values of the flux of the azimuthal component of the large scale solar magnetic field were calculated in the same way as the values of \( \phi_2 \); however the diameter of the circle was drawn in this case in perpendicular to the ecliptic plane.
Fig. 5. The same as in Figure 4, for the azimuthal component of the solar and interplanetary magnetic fields.

There may be of some interest, especially for the prediction of the state of the magnetosphere, some peculiarities in the development of the geomagnetic disturbances caused by the flare streams passing the Earth.

Returning once more to Figures 1–3, one can see that in accordance with our previous results, the flares which appear in the regions with $B_{sz} < 0$ cause sufficiently intensive geomagnetic disturbances accompanied by the development of strong DR-currents. In contrast to this, the streams associated with the flares that occurred in the regions with $B_{sz} > 0$ cause only compression of the magnetosphere and rather faint polar magnetic disturbances without any significant DR-current in
the magnetosphere. Thus the flares which appear in the regions with the southward magnetic field really may be considered as geoeffective ones, and the flares which take place at the regions with the northward magnetic field seem to be non-effective.

At the same time the data shown in Figures 1–3 are giving some evidence for the geomagnetic disturbances as well as for their time structure to be determined not only by the peculiarities of the solar flares but also by the characteristics of the background solar wind. Indeed, let us compare the course of the $D_{st}$ and $AE$ indices in Figures 2a and b, both of which concern the streams associated with the geoeffective flares. In the first case ($B_{wz} > 0$) one can observe after the passing of the shock front a rather prolonged period when the $D_{st}$ field is positive, which corresponds to strong compression of the magnetosphere and to rather weak DR-current. Intensity of the polar magnetic disturbances is slightly enhanced at that time (probably, as the result of intensive fluctuations of the vertical component of the magnetic field characteristic for the region of the compressed solar wind), however the most intensive agitation of the geomagnetic field and development of sufficiently strong DR-current are observed somewhat later, when the mean level of $B_z$ proves to be negative.

In the second case (i.e. when $B_{wz} < 0$) some compression of the magnetosphere is also observable, however the duration of that phase of the storm is relatively short, and the intensity of the polar magnetic disturbances reaches its maximum just after the passing of the shock front.

For the non-effective flares ($B_{zz} > 0$), the characteristics of the background solar wind play even more important role in the development of the geomagnetic disturbances. In this case the main body of the flare stream proves to be, as we have seen, non-effective. However if the background solar wind is carrying the southward magnetic field, this field, being increased by the coming flare stream, may cause sufficiently intensive disturbances. However, duration of those disturbances is rather short, and they are not followed by the development of any significant DR-currents.

3. Summary

The data presented and discussed above permitted us to arrive at the following conclusions.

(1) The flare stream or its head part at least are characterized by a magnetic field with significantly increased intensity. The region of the enhanced magnetic field (or the ‘magnetic region’ according to Ivanov et al. (1974)) coincides in its most part with the region of the compressed solar wind, although the field within the leading part of the main body of the flare stream seems to be also intensified.

(2) The vertical component of the interplanetary magnetic field within the flare streams has a regular part varying in a certain manner. So the field lines of the
flare stream magnetic field seem to be closed through the ecliptic plane up to distances of about 1 AU at least.

(3) The regular component of the flare stream magnetic field $B_{fe}$ is determined by the distribution of the large scale magnetic field at the Sun's surface. In particular, when the large scale magnetic field at the Sun is directed southwards at a flare region, the magnetic field within the plasma stream ejected by that flare is also directed southwards; hence such a flare and the stream associated with it are geoeffective. Similarly, the flares that occurred in the regions with a northward $B_{sz}$ and the streams caused by them are non-effective.

(4) The magnetic field within the 'magnetic region' of the flare stream is in essence the compressed field of the background solar wind and hence is not associated with the solar magnetic field at the flare region.

(5) Some peculiarities of the structure of the flare stream magnetic field seem to depend on the relative orientation of the magnetic fields within the main body of the stream and within the background solar wind.

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References