THE ROLE OF SHEAR MOTIONS IN THE PRODUCTION OF A PREFLARE SITUATION

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ABSTRACT. A rationale is presented for a conception that the appearance of flares in active regions is due to the interaction of large-scale convective elements. Such an interaction gives rise to shear motions in the vicinity of a zero line of the photospheric magnetic field which generate vortical motions leading to a nonequilibrium state of the magnetic configuration. The scheme we propose explains the cause-and-effect relationship between many observational signatures of the preflare situation. We have performed numerical calculations of the velocity field in an active region that produced a sequence of proton flares in August 1972, and the calculation results confirmed the proposed scheme.

ÚLOHA ZDVIHOVÝCH (SHEAROVÝCH) POHYBOV PRI VYTVÁRANÍ PREDERUPČNEJ SITUÁCIE. Interakcia veľkorozmerných konvektívnych elementov je považovaná za možnú príčinu vzniku erupcií v aktívnych oblastiach. Interakcia tohto druhu môže viesť k vzniku zdvihových (shearových) pohybov v okolí neutrálnej čiary fotosférického magnetického poľa a tým k vírovým pohybom vedúcim k nerovnovážnemu stavu magnetickej konfigurácie. Navrhnutá schéma vysvetľuje vzájomný vzťah medzi mnohými odpozorovanými znakmi prederupčnej situácie, ktoré sú uvažované ako príčina a erupcia ako ich dôsledok. Pre aktívnu oblasť z augusta 1972, ktorá viedla k vzniku protónových erupcií, boli uskutočnené výpočty rýchlostných polí. Výsledky výpočtu súhlasia s výsledkami navrhnutej schémy.

The dynamics of the magnetic field and matter in photospheric layers of the solar atmosphere is determined by a complicated interaction between structural features of various scales. There exist a three-stage hierarchy of convection, namely granulation, supergranulation and large-scale structures (1) consisting of elements with characteristic scale of sizes, lifetimes and mass velocities in therm. A combination of such structures, together with the differential rotation of the Sun determines the complicated picture of the veloci-

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ty fields observed and manifests itself in the evolution of magnetic configurations such as complex of activity, active regions and individual sunspots, and, evidently, influences the flare activity. It is known that large active regions are, on an average, concentrated near the boundaries of large-scale structures, giant cells (2). Flare activity is also concentrated at the boundaries of the cells involving 1 or 2 supergranules (3). Many authors point to a relationship of flares with horizontal shear motions in the vicinities of the inversion polarity line (IPL) of the photospheric magnetic field (4, 5). That flares are associated with emergence of new magnetic flux in the active region has been also confirmed by observations (6, 7). These two kinds of relationship were usually studied separately; recently, however, attention was drawn to a correlation of shear motions with emergence of new magnetic flux. The chromosphere over the IPL often shows dark filaments which delineate definite boundaries separating the structural features and their activation serves as one of the signatures betoking the appearance of a flare. Peculiarities of the orientation of dark filaments and bendings of the IPL also are flare predictors (8).

IPL deformations may arise as sunspots are moving perpendicular to the IPL (4). There are indications that rotational motions of the sunspots are associated with the production of surges (9). It has been established that the flare production is favoured best by a situation when the IPL and the zero isoline of line-of-sight velocity intersect and the latter abruptly changes its direction (10).

The same authors (11) found that some configurations of the line-of-sight velocity distribution, interpreted as being horizontal vortices, may coincide with places of sunspot appearance or disappearance.

Thus, within structures of moderate and small scales, manifestations of solar activity are more frequently observed near the boundaries of these structures. In the case of larger scales, the idea that active regions and complexes of activity appear near the boundaries of corresponding structures such as the IPL and tangential discontinuities of horizontal velocities, does not seem unusual, though observational evidence accumulated so far is not yet sufficient. An at least outward analogy suggests itself between the above-mentioned phenomena and the concentration of seismic activity in the zones of fractures on the boundaries of the Earth's crust plates, as indicated by geotectonic data.

Analysis of the above-mentioned observational data leads to the following physical picture of cause-and-effect relationships producing a preflare situation and, then, the flare itself. Shear motions (the Coriolis force effect in supergranules, for example) are almost always present on the boundary of neighbouring elements of any of the scales indicated. The evolution of such tangential discontinuities gives rise to a system of vortices in their neighbourhoods. Since the boundaries of structural elements sufficiently frequently coincide with the IPL, horizontal vortical motions of matter are able to cause local enhancements of the frozen-in magnetic field near the IPL and, therefore, accumulation of extra (nonpotential) energy in the magnetic configuration, current sheet formation, and - during a relaxation release of this energy via

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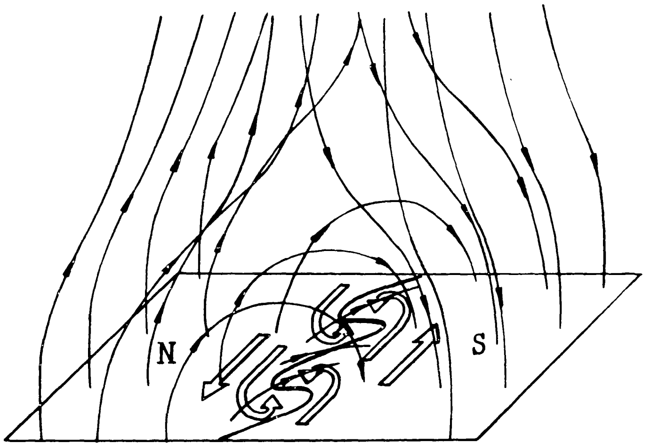

Fig. 1: Magnetic field configuration above the photospheric plane and the horizontal velocity field in the vicinity of the inversion polarity line (IPL). Legend: ------- the inversion polarity line;
--- -- magnetic field lines;
the direction of mass motions in the photospheric plane.

any suitable mechanism - flares. This scheme is illustrated by Figure 1. Additional energy in magnetic configurations is supplied by hydrodynamical motions in structural features with a scale well above that of a flare region so that energy sources are virtually inexhaustible for such disturbances. This mechanism can "work" both in active features of various scales, viz. complexes of activity, active regions, individual sunspots, and others, and outside their flare outside active regions. Also, the proposed mechanism permits the physical content to be determined for a number of signatures of the preflare situation: the appearance of bending deformations of the IPL, emergence of new magnetic flux, filament activation, etc. Of course, the scheme thus presented needs further development. First, it is necessary to appeal to additional observational data on velocity field characteristics in the photosphere in the vicinity of the IPL. Second, a theoretical analysis ought to be made of the extant flare models in order to modify them with proper allowance for the proposed mechanism of magnetic energy accumulation. In particular, there are already results available lending support to this scheme. A mass shear flow along the IPL was found from chromospheric and coronal (UV) lines (12). There is also reported observational evidence for the relationship of flares with the magnetic field shear structure, and the rate of magnetic energy accumulation in such configurations was estimated at 2.10^{30} - 10^{32} ergs/day for a typical active region, which is quite sufficient for the flare energetics (13).

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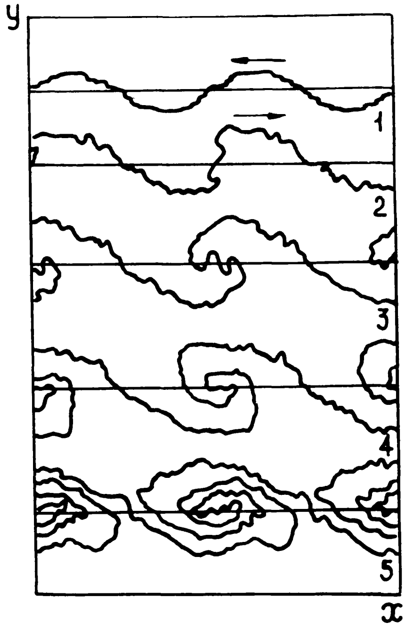

Fig. 2: The evolution of a sinusoidal disturbance in the tangential discontinuity of velocity, according to calculations in (15).

Now, let us consider some other arguments. It is known that a Kelvin-Helmholtz instability arises provided there exists in a flow of liquid or gas the relative slip of the neighbouring layers. At sufficiently large Reynolds numbers, such motion is unstable - on the boundary separating the media there appears a system of vortices the scale of which is comparible with the width of the transition region (the linear stare of instability development). A nonlinear interaction between minor vortices generates vortices of increasingly larger scales (the nonlinear stage). Numerical simulation results on two-dimensional motion of the gas being compressed (14-16) show that the boundary of the tangential discontinuity of velocity, originally shaped as a sinusoid, is evolving as shown in Figure 2 (from /15/), i.e. separate protrusions are deformed by a flow of the gas and are twisted like spirals. For a well-developed small-scale turbulence in the solar photosphere, the effective viscosity $\nu_t \approx 10^{12}$ cm^2 s^{-1} and the Reynolds number, estimated in terms of scale L and velocity U of the supergranule, is $Re = \frac{UL}{\nu_t}\ 10^2$, i.e. is, no doubt, smaller than a critical value. Hence, along the supergranule boundaries the boundary layer does not split into two. Therefore, an excitation of vortical motions on the separation boundary requires disturbances of finite amplitude which abound in the photosohere.

Let us considere a very simplified model of frozen-in magnetic field va-

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riations, caused by the horizontal velocity field, on time intervals of several hours where magnetic field diffusion can be neglected (17). According to Stern (18), the velocity $\vec{V} = (u, v, w)$ conserving the magnetic flux, must satisfy the relation

$$\vec{Q} = \frac{\partial}{\partial t}\vec{B} - \text{rot}\ (\vec{v} \times \vec{B}) = 0 \qquad (1)$$

Taking into account $\text{div}\vec{B} = 0$ the z-component involved in this expression, is transformed to the form

$$\frac{\partial}{\partial t} B_z + \text{Div}\ \vec{S} = 0 \qquad (2)$$

where we have introduced a two-dimensional vector $\vec{S} = (uB_z - wB_x,\ vB_z - wB_y)$ and a two-dimensional differential operator $\text{Div}\ \vec{a} = \partial a_x/\partial x + \partial a_y/\partial y$. This equation is also satisfied by a vector of the form $(S_x + \partial A/\partial y,\ S_y - \partial A/\partial x)$, where A is an arbitrary scalar function of coordinates and time. The A-dependent terms have no effect on the time-variation of flow B_z and describe the displacement of individual magnetic field lines without breaking the spatial distribution of flow B_z, i.e. describes an equivalent rearrangement of any pair of field lines. Since we are considering a plane motion, it is necessary to put $w = 0$ so that $\vec{S} = B_z\vec{R}$, where $\vec{R} = (u, v)$.

Equation (2) may be solved for $\vec{S}$ by a variety of methods, namely by applying the conservative finite-difference scheme (19) by reducing this equation to a Poisson equation and using the Green function (17) or by realizing a locally smooth approximation of $\vec{R}$. All of the three variations have their merits and disadvantages and need a special analysis of the peculiarities inherent in them. We have to find a velocity field R from observational results on time variations of B_z in areas of the solar surface. Since S is a solution of the inverse problem and when $B_z = 0$ the value of R becomes uncertain, it seems appropriate to find R by the regularization method (20) by sampling the regularization parameter of order B^2_{cr}, where B_{cr} is the noise level in B_z - observations. Two-dimensional differential characteristics of the velocity field in the vicinity of the IPL ($B_z = 0$) are physically meaningful: to vortices ($\text{Rot}\vec{R} \neq 0$) there correspond segments of bending deformations of the IPL, to source and sink regions ($\text{Div}\ \vec{R} \neq 0$) - areas of magnetic flux emergence and submergence (17), and to extrema of the value of $\varepsilon = (\partial u/\partial y + \partial v/\partial x)/2$ - areas of rapid variations of hydrodynamical stresses (21).

It is clear that the decisive role in studying the velocity field in the vicinity of the IPL from observational data on B_z, as has been explained above, is played by the accuracy of local determination of $\partial B_z/\partial t$. Then, the following requirements should be imposed on initial data. First, in order to reveal the process of energy accumulation before the flare and the relaxation process after the flare requires a series of 2 to 4 magnetograms taken before the flare and of 2 to 4 magnetograms thereafter. The flare must be of moderate importance, a single one, and well documented from other data. Second, from estimations of the accuracy of measurement of magnetic fields and typical velocities

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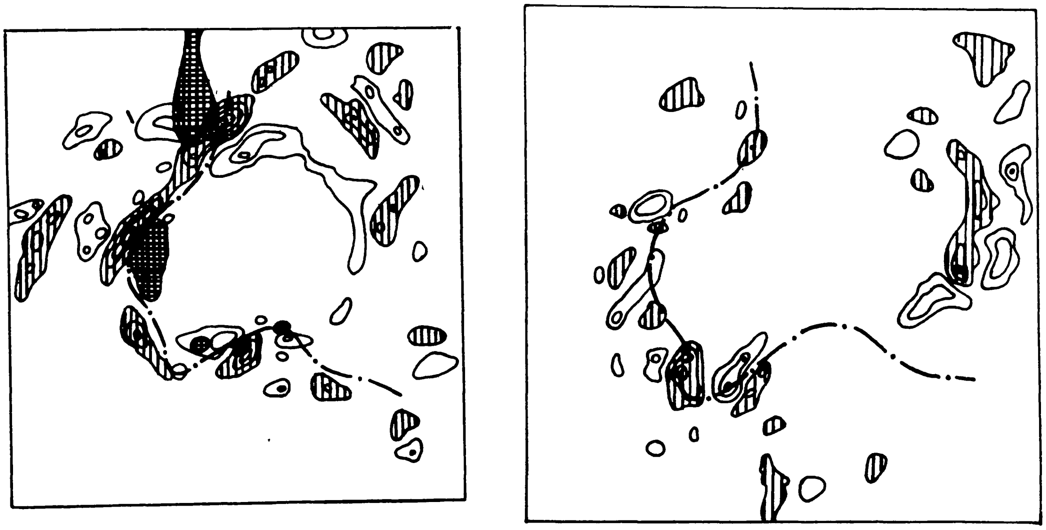

Fig. 3 Fig. 4

Growth rate distribution of shear deformations for the steps in time from 2 to 3 August and from 3 to 4 August, respectively. ε isolines are drawn for the values of ± 10, 20, 30 1/day. Areas of positive ε are marked by vertical hatching. A dot-and-dash line marks the mean position of the neutral line. Acrosshatched area indicates the original position of flare knots (22).

of matter in the photosphere it follows that intervals between magnetograms must be 5 or 6 hours at least. Third, magnetograms must be uniform in the calibration and must have a unified coordinate basis.

Unfortunately, we have presently unavailable any material satisfying these reguirements. However, we have done preliminary calculations for B_z - magnetograms from the Kitt Peak observatory, for a large August 1972 group (2 AUG 22:07, 3 AUG 23:09 and 4 AUG 14:08 UT) which were published by Levine and Nakagawa (21). In the calculations, $\partial B_z/\partial t$ was approximated by the ratio $\Delta B_z/\Delta t$. Figure 3 and 4 give the distribution of the value of ε and the mean positions of the IPL for two pairs of the IPL for two pairs of magnetograms, 2-3 and 3-4 August. Figure 3 presents a picture before the 4 August flare; cross-hatching denotes the location of the emission kornels of this flare at its onset time at 06:24 UT, according to data reported by Beeda et al. (22). Extrema of ε are concentrated near the IPL; before the flare they are large in magnitude and the flare emission kornels coincide quite well with them. After the flare (Figure 4), the extrema of ε are more scarcely arranged and are smaller in magnitude (23) . The picture itself of their distribution agrees with data of Zirin and Tanaka (4) on the position of areas in which the magnetic fields is shea-

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red, obtained from H_α-filtergrams. Thus, these results agree, in general, with the proposed picture of the appearance and development of a preflare situation.

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COMMENT AND DISCUSSION

M.A. Mogilevsky

Термин "шир" в физике плазмы означает градиент сдвиговых движений на относительно нескольких уровнях, т.е. если S_1-угол на уровне Z_1, а S_2 на Z_2, то широм считается величина

$$\eta = \frac{S_2 - S_1}{Z_2 - Z_1} \qquad \frac{\Delta S}{\Delta Z}$$

Если имеются данные о движении на одном уровне, то лучше употреблять термий сдвиговые движения, а не шир.

J. Staude

In your analysis you assumed that the vertical motion is equal to zero ($w=0$), but with magnetograph we can measure the line-of sight velocity. Could you estimate how a violation of the assumption $w = 0$ could modify your results ?

G.V. Kuklin

Во первых, мы оперируем с понятием скорости, сохраняющей магнитный поток и определенной только на поверхности нормальной к магнитным силовым линиям. Эта скорость отличается от обычно измеряемой массовой скорости (bulk velocity) и имеет другой физический смысл. Во вторых, мы не знаем средств для прямых наблюдений компоненты скорости w, т.е. измерений смещения магнитного поля приблизительно вдоль самих силовых линий. В-третьих, наша схема может учесть эффект $w = 0$, если доступна информация о всех трех компонентах вектора напряженности магнитного поля и их производных по времени и координате z. Такие данные сегодня фактически отсутствуют.

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