PART IV.

Considerations on Localized Velocity Fields in Stellar Atmospheres: Prototype — The Solar Atmosphere.

C. - Transient Velocity Fields in the Lower Solar Atmosphere.

Summary-Introduction.

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1. – Introduction.

Speaking on localized velocity fields on the Sun, we mean the velocity fields in active regions on the disk. The experimental data used to picture these fields are based mainly on 1) the observations of Doppler shifts of spectral lines, 2) the form (asymmetry) of line profiles, 3) moving picture process in monochromatic, mainly H_α and H or K, light. However the big skin-time of solar plasma makes these data insufficient to get an adequate and complete idea about the motions in active regions, and we must also take into account the available observational data about magnetic fields in these regions. Somewhere the state of affairs permits one to disregard the possible influence of magnetic fields on the picture of velocity fields $(H^2/8\pi < nkT$ or $\frac{1}{2}\varrho v^2)$. But these occasions are comparatively rare, because the main source of solar activity is closely, but in a not quite recognized way, connected with magnetic activity of the Sun. This is why we should in our talk consider as closely as possible both subjects—the motions in active regions and their magnetic fields. The best illustrations of the necessity of such a mode of consideration are the velocity fields in sunspots.

2. – The velocity fields in sunspots.

Peculiar motions in sunspots were discovered by EVERSHED (1909, 1910) and were considered as in-streaming of gases towards the axis of the spot in outer layers and out-streaming in deep layers. ABETTI (1932, 1934) found an azimuthal component in this motion and indicated a possibility of spiral-like motions. The vortex structure around spots, as seen on H_α-spectroheliograms, induced the idea about vortex motion around sunspots (HALE, 1908; BJERKNESS, 1926) like Earth cyclones and this can easily be supported by a simple

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consideration of the action of Coriolis' force on the Evershed motions. However we don't have as yet direct observational evidence of such vortex motions; and the vortex structure, which is unique rather than typical, is considered as a manifestation of the peculiar character, of the magnetic field around spots.

The observations at McMath observatory (McMath, Pierce, Mohler, Goldberg, 1956) and the extensive and detailed investigations of the Evershed effect carried with the aid of the Crimean Solar tower by Bumba (1959, 1960) revealed the fine spectral structure of this phenomenon. It appears to be not a kink of a line but a broadening as a whole, with strongly pronounced asymmetry of opposite directions at the opposite borders of penumbrae. At perfect conditions of seeing, this asymmetry is simply a jet-like component—« flag » is similar to that produced by a spicule, and instead of « flags » we observe sometimes a separate component—a secondary faint satellite of the line. At bad seeing and low resolving power this phenomenon of « flags » disappears, and we observe the usual Evershed pattern, *i.e.* the kink of the line (*). The maximal velocity measured in « flags » reaches $(7 \div 8)$ km/s, and the tilt of velocity vector to the solar surface increases with increasing depth (the Michard model was used to determine the effective depths of different lines). If the plasma is able to move across the lines of force with such velocities (despite the fact that $H^2/8\pi > \frac{1}{2}\varrho v^2$) the whole magnetic field of the sunspot can be disintegrated during 10^9 cm/$8 \cdot 10^5 \simeq 10^3$ s, which time is too short for the life-time of a sunspot. This strongly suggests that these motions proceed along the lines of force of the magnetic field forming something like a « fan ». The following picture of motions resembling the behaviour of integral curves near a saddle point seems to be the most probable one (Fig. 1), and the most interesting is the change of the direction of motions near the boundary between the photosphere and chromosphere and the growth of velocity from this boundary downwards and upwards.

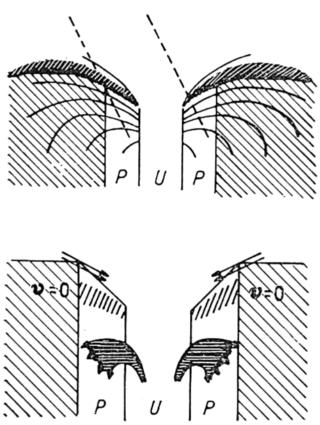

Fig. 1. – The pictures of magnetic field (above) and motions (below) in spot (P: penumbrae, U: umbrae).

The fact of opposite directed motions (instreaming) in the outer layer (chromosphere) of the sunspot has also been checked directly by the author, who used the magnetograph to record the magnetic fields and line-of-sight velocities simultaneously in the chromosphere *above the limb* for the spot immediately near the limb (Fig. 2). From the run of line-of-sight velocity and radial component of the magnetic field one can easily draw

(*) This effect is most pronounced, as is well known, at the border of the Sun, when the slit is set along the radius.

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the conclusion that the change of magnetic polarity is accompanied by the change of radial velocity as if the flow of plasma proceeds along the lines of the magnetic field of the sunspot (SEVERNY, 1960*b*).

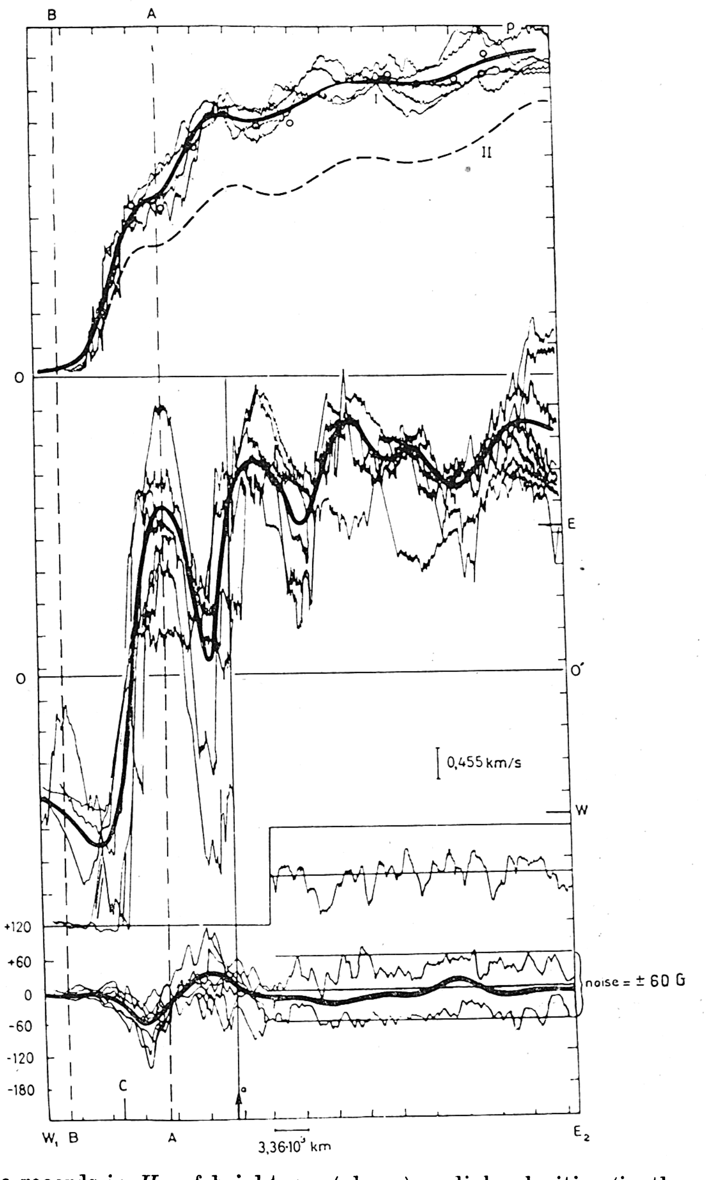

Fig. 2. – The records in H_β of brightness (above), radial velocities (in the middle) and magnetic field (below) for the spot July 24, 1959 near limb (dashed vertical line AA). Arrow a and full vertical line correspond to the spot; BB: the top of hydrogenic chromosphere; OO': corresponds to zero velocity on the Sun. Vertical scale of the field in gauss.

These conclusions are mainly based on the observations outside umbrae. However the observations of CHEVALIER (1913) and THISSEN (1950) indicated the possible existence of fine structure in umbrae—a kind of granulation. Our attempt to examine with the aid of the high resolving power magnetograph ($2'' \times 2''$) the fine structure of the umbrae showed clearly the existence of separate condensations of field lines-of-force inside umbrae, the condensations with characteristic size of several seconds of arc (see Fig. 3). But the most striking phenomenon is the appearance of a pure *transversal* field in the middle of the umbrae of the big spot near the center of the disk, observed in perfect conditions of seeing. This fact may be considered as evidence that convection still exist in the very umbrae (private communication of Prof. COWLING) and the spreading of the ascending current dragging the frozen magnetic field with it in horizontal plane produces the effect of transversal field. But the appearance of Zeeman triplet in umbrae may as well also be connected with the depolarization effect due to fluctuations of magnetic field with depth or due to depolarization by collisions (SEVERNY, 1959).

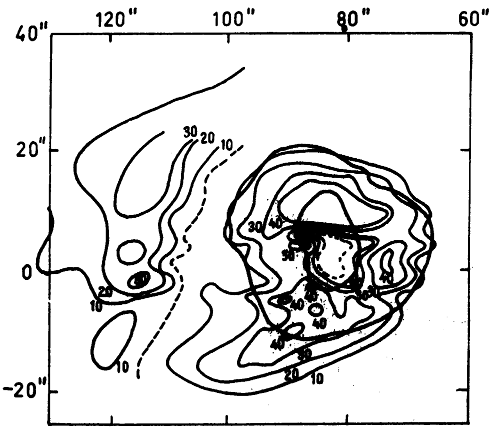

Fig. 3. – The map of isogauss for big spot Sept. 26, 1958 near the center of the Sun. The unit is 15 G. Dashed closed line is neutral line. Heavy full line is contour of umbrae and penumbrae.

In any event the velocity field in the sunspot must be closely connected with the structure of the magnetic field ($H^2/8\pi > \frac{1}{2}\varrho v^2$ for the most part of sunspot plasma) and this field plays a primary role in all phenomena over here. It seems improbable that this field is pure longitudinal because of instability of such field—it must expand. We may consider the observed fine structure of the field in umbrae as a manifestation of such instability of pure longitudinal field. We think the force-free field or similar to that is the most probable configuration of a stable magnetic field of sunspots and for securing the long life of sunspots. This conception offers also the possibility to explain the observed vortex-cyclonic structure around sunspots and spiral-like motion inside the spots.

3. – The motions of flares.

At first flares were considered as stationary formations (ELLISON 1949). First evidence of motions in flares was obtained for flares of May 15-16, 1951 at McMath (DODSON and McMATH, 1952) and Crimean Observatories (SEVERNY

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1952*b*). The expansion of flare area accompanying the growth of H_α-intensity might be considered as a spreading of excitation. However the spectroscopic observations of line-of-sight velocities in flares indicate real motions of neutral hydrogen in flare regions. Let us consider first the data from the moving picture technique in H_α-light.

On the disk, except for expansion of the flare region, about 30% of flares show the rapid motions of jets or plasmons (SEVERNY and SHAPOSHNIKOVA, 1952, BRAY, LOUGHEAD, BURGESS and McCABE, 1957) with supersonic velocities. Sometimes in great flares at their further development, we can observe the motions of luminous fronts or shells moving with supersonic velocities ~300 km/s and the bending of these fronts when they approach sunspots. The course of events is nearly the same as if some shock-wave were partly reflected by the magnetic field of the sunspot. There is a similarity in the motion of these fronts and shock fronts; namely, the thickness of the luminous front (or intermediate layer) decreases with increasing velocity according to approximately the same dependence in both cases (GOPASUK, 1958).

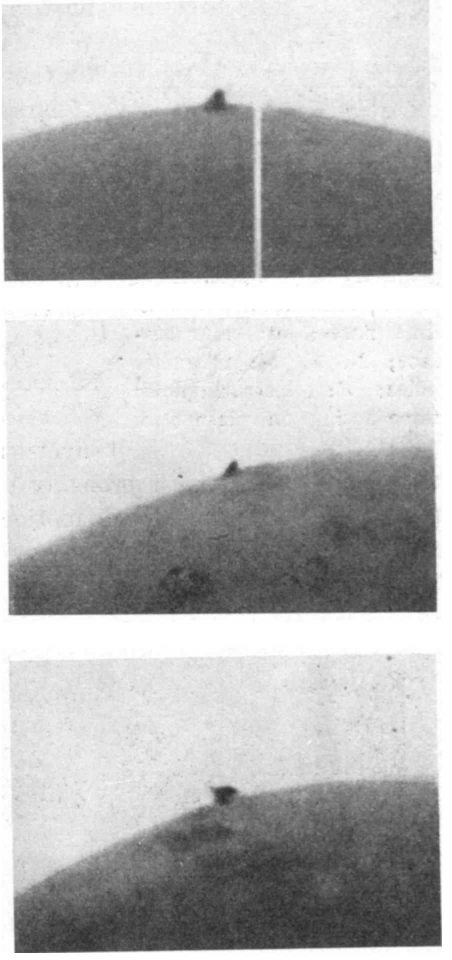

Fig. 4. – The typical limb flares.

However the most important data may be obtained from the observations of flares above the limb. More than 25 limb-flares from 180 observed with the Crimean coronograph have been considered in detail; and for 14 flares the motions, brightness and area were measured (SEVERNY and SHAPOSHNIKOVA, 1960).

It was found that a great majority of flares above the limb appear as a brilliant hill (with sharp conical edge, Fig. 4), the upper front of which undergoes a rapid dilatation and after that a contraction with velocities from 50 km/s to 600 km/s. These dilatations are not uniform but show pulsations. The corresponding accelerations are very high ($5 \cdot 10^4$ to 10^6 cm/s^2). The most characteristic is a « *cumulative* » *effect* on the upper edge of the flare (the for-

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mation of a conelike top) and its successive contraction excluding the conception of the flare as a simple explosionlike phenomenon. (It is interesting to note that the rate with time of the distance of the upper edge from the original « core » of the flare is considerably higher than that observed at nuclear explosions (TYLOR, 1950)). The cumulativity of explosionlike flare-prominences can be explained by the peculiar geometry of the crossed magnetic field (cusped-field geometry) surrounding the flare, which appears in neutral point of this field due to the pinch-effect. A high-temperature plasma of flare trapped in this case in a « magnetic bottle » tends to expand in the direction of least counteraction from the surrounding field (on Fig. 5 shown by arrow). The electrodynamical acceleration of a current appearing in the neutral point can attain observed values at the strengths of 100 G of surrounding field.

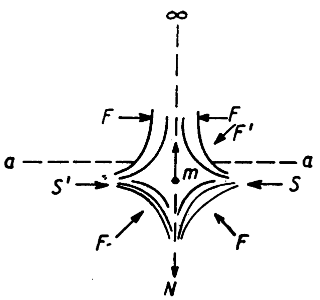

Fig. 5. – The cusped field geometry of magnetic field to explain the motions in limb flares; *aa*: solar surface; *N*, *S*, *S'*: magnetic poles; *F*: electromagnetic force acting on plasma *m*.

Therefore moving-picture records show that in flares we deal with the formation of *cumulative jets* of plasma (or plasmons), moving with supersonic velocities, and exerting a supergravitational acceleration most probably under the action of electromagnetic fields. (Something like plasmotronic motions *e.g.* of the type realized by KOLB (1958) and ARZIMOVICH, LUKJANOV, PODGORNY and CHUVATIN (1957)).

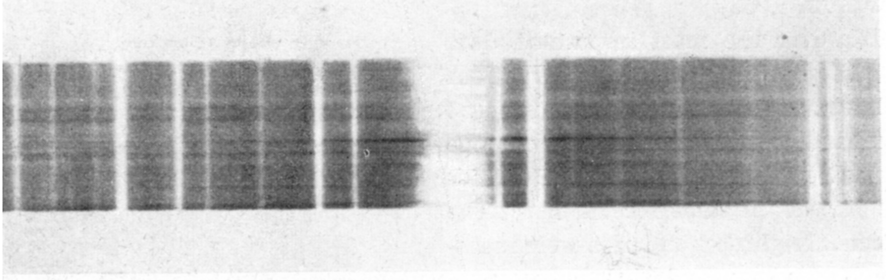

Fig. 6. – The « Moustaches » in H_α.

Turning to the spectroscopic observations we should at first consider the phenomenon of fine structure of flare emission, or of moustaches, out of which the extremely extensive wings of H_α-lines in great flares are composed (SEVERNY, 1957 *a* and *b*). Besides, the phenomenon of moustaches has its own importance in the problem considered. The spectroscopic investigation of moustaches (Fig. 6) showed that the far wings of lines originating in the very

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« core » of a flare, may be considered as broadened owing to the Doppler effect of some kind of « macroturbulence » with velocities from 80 to 250 $km \cdot s^{-1}$. The most convincing evidence for this can be found in limb flares. If the emission of far wings is optically thin and broadened by Doppler effect, the velocities of atoms in this process can reach 1000 or more km/s.

In most of the cases, the blue wing of moustaches at the disk is brighter and broader than the red one, which may be considered as an evidence of ejection of atoms out of the grains of peculiar emission. This asymmetry does not depend on the position on the disk and indicates that the process of ejection is similar to explosion predominantly in two opposite directions, and not to a process of pure radial ejection. This is confirmed by the appearance of moustaches tilted to the plane of dispersion. The phenomenon appears at different levels in the solar atmosphere, and when it is found in deep layers the undisturbed absorption line is shifted to the violet indicating velocities $\simeq 3$ km/s lifting up these grains of emission.

Fig. 7. – The typical emission in core of H_α-line in flares.

All the above-mentioned spectroscopic phenomena relate to the outermost part of lines; *i.e.*, to the regions of high Doppler velocities. The inner part—the core of the line in flares—shows often an asymmetry; and the most typical form of this asymmetry is the predominance or excess of emission in the red side. The emission is stronger and more extensive over the disk in the red side of the line than in the blue side, however the blue part of the line is more extensive along the spectrum (see Fig. 7). This indicates the complex character of the motions—presumably the contraction and expansion (see below) of flare plasma. The contraction of the region of continuous emission in flares was also observed by ZIRIN (1959). These facts are compatible with moving picture data and can be explained by ideas about pinch-effect (see below).

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Summarizing briefly our observational data about *magnetic fields* connected with flares, we can state the following (SEVERNY, 1960*a*).

1) Flares appear practically *in neutral points* of magnetic field of spot groups ($H = 0$, $\nabla H \geqslant 0$). This was observed in 54 cases out of 61; in 7 cases the discrepancy is bigger than errors.

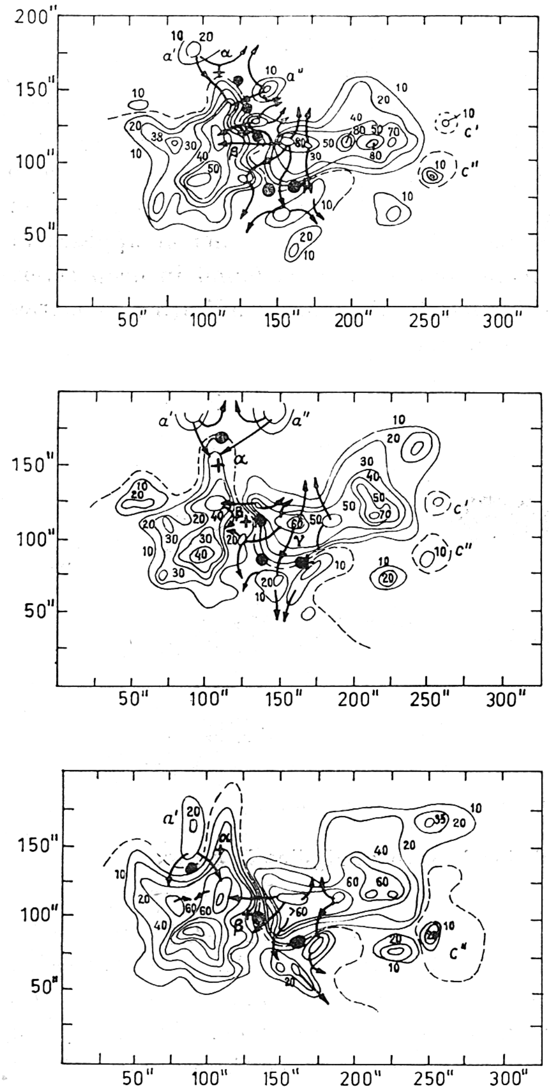

Fig. 8. – The successive maps of magnetic fields recorded in λ 4886 before and after the flares of importance 2^+ and 3, Aug. 22, 1958 showing the simplification of field after flares. (Unit = 10 G). Full dots: neutral points, crosses: locations of flares at their origin. Dashed line: neutral line. Arrows: approximate directions of field tubes.

2) The flare phenomena lead to *simplification* (or « destruction ») of fields surrounding neutral points—the reducing of ∇H, the vanishing of nearby magnetic hills, etc. This process was observed in 7 cases out of 8.

3) For six flares, besides that, GOPASUK has recently observed *the contraction* of configuration of distant magnetic poles after the flare.

See Fig. 8 illustrating these results.

These facts led us in 1957 to the idea about the *transformation of magnetic energy* into heat energy in flares. If the distribution of the field near neutral points looks like that presented on Fig. 9, the plasma contracts near the neutral point until two shocks approaching the neutral point appear. The collision of these shocks heats the plasma impulsively in a small region up to $T \sim (10 \div 30) \cdot 10^6$ °K. This is a kind of pinch-effect.

One of the most suggestive observational data in favour of this point, beside the data

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mentioned above, is the records of line-of-sight velocities which show that neutral points of H are practically always (in 30 cases out of 37) found on the neutral lines of velocity maps—in places where two motions have opposite velocities and where they are often off the scale of the recorder (very steep change of velocities), see Fig. 10 showing maps—one of magnetic field and the other of radial velocities.

In case of two *distinct* layers approaching or escaping each other we should observe the splitting of a spectral line. But in the case of a contraction continuously distributed around the neutral point we will have predominance of +velocities from one side and — velocities from the other side of the neutral point. The undisturbed matter between two shocks is pushed away from the neutral point in both opposite directions perpendicular to the motion of shocks, and this presumably produces the observed phenomenon of moustaches and the steepest change of velocities near neutral points.

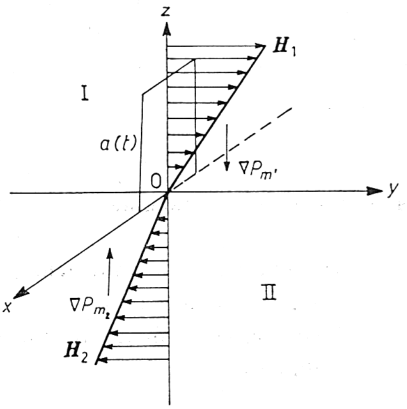

Fig. 9. – The distribution of field strength near neutral plane XOY leading to pinch-effect, (see SEVERNY, 1958).

Pinch-effect around the neutral point in the free-field can be set up by the annihilation of azimuthal fields of approaching force tubes with opposite longitudinal fields (see for instance GOLD and HOYLE (1960)). The contraction of plasma in the region of the neutral point can also be produced by rapid

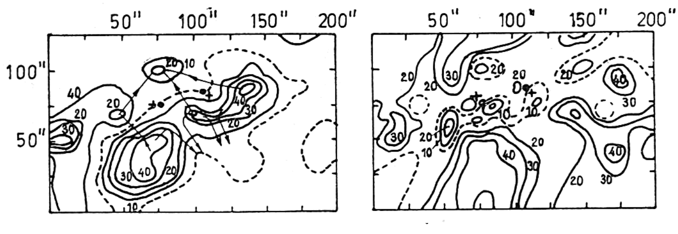

Fig. 10. – The maps of magnetic field (left) recorded in H_β and radial velocities (right) of the same active region. The notations are the same as on Fig. 8.

changes of sunspot fields if these fields are external, of dipole character. In both cases strong shock-waves converging to the neutral point can appear. It was shown that the incident shock front outruns the region of strong magnetic field. As a result of reflection of incident shocks in the neutral plane the stationary high temperature region is formed behind the front of the re-

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flected shock moving in the contracting plasma towards the region of strong magnetic fields (SEVERNY and SHABANSKY, 1960). The magnetic energy is thus used up for heating this region and this heating may cause thermonuclear reactions in flares. The undisturbed plasma between approaching shocks will be pushed in two opposite directions perpendicular to the direction of shock motion. These considerations can explain some principal features of observed phenomena including the generation of cosmic rays (SEVERNY and SHABANSKY, 1960).

4. – Flocculi and faculae.

BABCOCK was the first who found a connection between calcium flocculi and magnetic fields (BABCOCK, 1960). STEPANOV confirmed this result and examined velocity fields in flocculi with the following results (STEPANOV, 1958, 1960):

1) Stationary descending motions are observed over the 80% of the area occupied by flocculi and the corresponding mean velocities are

$$V_{\text{desc}} = +1.7\ \text{km/s},$$
$$V_{\text{asc}} = -1.0\ \text{km/s}.$$

It follows that the excess in flux $S \times V$ is 4 times in descending motions as compared with the ascending one.

2) The observations of flocculi *near the limb* showed the *inflow* of gases into the region occupied by flocculi and this inflow is 10 times smaller than inflow through the upper boundary. This excess of inflow is probably compensated by outflow of matter during non-stationary processes such as flares and surges; and an approximate picture of the motions is shown in Fig. 11.

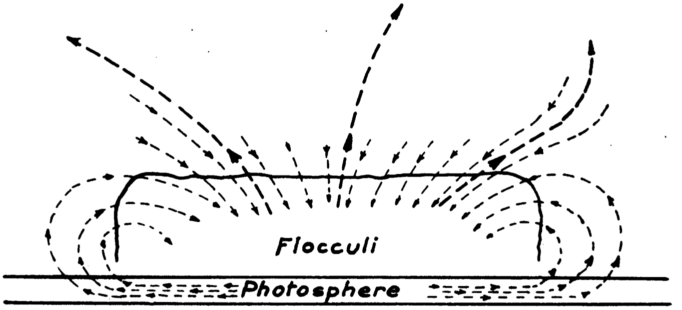

Fig. 11. – The approximate picture of motions in flocculi.

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These relates to Ca^+ chromosphere. In *deep layers* (photosphere) the picture depends on the strength of H; and STEPANOV found that for strong $H > H_0$, the direction of motions follows closely the magnetic polarity as well as the line of zero velocity, which is similar in form and position to the neutral line of H. The example is in Fig. 12.

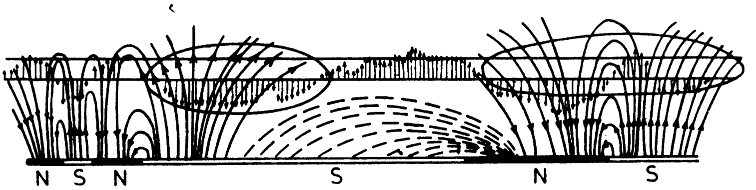

Fig. 12. – The correspondence between motions and magnetic fields (at considerable strength) in faculae.

If H is weak only descending motions are observed independently of polarity of magnetic fields.

These results indicate that the motion of plasma in flocculi and faculae is governed by the magnetic field only if this field is strong enough. In the opposite case we have in-streaming of gases into the region of flocculi.

To explain the connection between magnetic field and the active regions including faculae, PICKELNER has recently pointed out that the weak field increases the stability of convection streams and decreases the turbulent viscosity in the upper layer of the Unsöld zone. It should increase the convection velocity, which explains a small gradient of temperature in faculae, the increase of the flux of acoustic energy, and the heating of the chromosphere and the corona above active regions. The further increase of magnetic field may stop convection in the way described, for instance, by BIERMANN (1941).

5. – Prominences.

Here we have the most clearly defined motions of the solar plasma. The proposed classification of prominences according to the predominant type of motion in them (SEVERNY, 1952 and SEVERNY and KHOKHLOVA, 1953) seems to possess a general physical meaning, although it does not reflect all peculiarities of motions and behaviour of phenomena. The turbulent or irregular motions which are characteristic for quiescent prominences are developed, as a rule, far away from strong magnetic fields. The hystogram of these motions (the number of knots *vs*. velocity) as compared with the two dimensional cross-section of a Maxwellian distribution shows considerable deviations of these irregular motions from the usually adopted picture of astronomical turbulence. DUBOV (1955) found this irregular behavior of quiescent prominences may be described in terms of locally-isotropic turbulence with a Kolmogorov spectrum.

In the presence of strong magnetic fields, *e.g.* that of sunspots, the predominant type of motion, on the contrary, is the « electromagnetic » one—the movements of knots and streamers proceed along curved paths nearly corresponding to the lines of force of nearby magnetic fields (CORELL, HAZEN and BAHNG, 1956; see also: SEVERNY, 1952; SEVERNY and KHOKHLOVA, 1953). Here the motions are mainly uniform, except those parts of trajectories where the mass is detaching from the main body of prominence or streaming into the « center of attraction », where it is substantially accelerated sometimes up to supergravitational values (BARTLETT, WITTE and ROBERTS, 1953). Finally, the eruptive and tornado prominence show peculiar motions sometimes like a spiral running along the conical surface (resembling the motion of a charge in the field of « isolated » magnetic pole) or along a cylinder (ROTSHILD, PECKER, and ROBERTS, 1955). Some attempts were made to explains these motions as result of diamagnetic repulsion of a big mass of plasma from nearby increasing magnetic field (JENSEN, 1959; see also SEVERNY and KHOKHLOVA, 1953). One peculiarity of prominence motions should be kept in mind. In loops and some eruptive prominences, we often observe a dilatation of the stream as if the ascending and descending motions coexisted together in one stream. This dilatation may sometimes lead to confusion on the real motion of the knot or streamer as a whole with the motion of the front of a knot. We think that this is the cause of the abrupt changes of velocity measured by PETTIT in eruptive and some other prominences.

The spiral-like motions in prominences can be explained if the velocity vector is tilted to the magnetic lines of force, and a current along the direction of motion appears. The mean free path of ions is considerably larger than that of electrons, and if it is compared with the size of the knot, the electrons will be decelerated and the knot will consist mainly of rapid ions and slow electrons that give rise to a current. The motion of this element of current is nearly the same as the motion of individual charged cloud of particles, and so it proceeds along spirals in the field of a magnetic pole (PICKELNER, 1956).

The problem of forces producing the observed motions of prominences remains still obscure; however, there is hardly a doubt about their electromagnetic nature, and supergravitational accelerations and the reverse motions along the same curved path (surges) are the best manifestation of the peculiar character of these forces. Another phenomenon for further explanations is the ability of prominence material to *cumulate* into jets and knots; however, something like a pinch-effect in the presence of azimuthal or toroidal magnetic fields might be used for explanations.

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