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ON A TWO-COMPONENT MODEL OF THE MAGNETIC FIELD AND THE VELOCITY FIELD IN A SUNSPOT

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1. Introduction

The magnetic field and the velocity field in the penumbra of a well-developed sunspot has a fine structure. However, most of photoelectric observations of magnetic fields and line-of-sight velocities in sunspots are currently made with a low spatial resolution of 1"-2". Results obtained are treated in terms of a homogeneous penumbra, which leads, on occasions, to contradictory conclusions. This refers, in particular, to the question of the magnetic field frozen-in to the plasma in a sunspot. Observations reported by Kotov [1], for example, show a good coincidence of zero lines and hills of field and velocity, thus giving evidence for the frozen-in field. We, however, [2] observed their spatial negative correlation when the line-of-sight velocity maximum ($V_{\parallel}$) lies near the zero line of the longitudinal field ($H_{\parallel}$). Although the mass motion in a sunspot across magnetic field lines does contradict the theory, the very fact of the lack of coincidence of zero lines $V_{\parallel}$ and $H_{\parallel}$ was observed by many investigators (for the first time, obviously, by V.E.Stepanov [3]) and is, probably, the usual property for a sunspot with a well-developed penumbra. Kuklin and Stepanov [4] identified such a non-coincidence with the motion of the magnetic field, while Maltby and Eriksen [5] attributed it to the presence of an acoustic wave propagating across magnetic field lines. A.B.Severny in his recently published book [6] suggests that the plasma in a sunspot can penetrate into the space between field line ropes.

In this paper an attempt is made to explain the contradictions, associated with the frozen-in condition, in terms of a two-component model of the magnetic field and the velocity field in a sunspot.

2. Observations

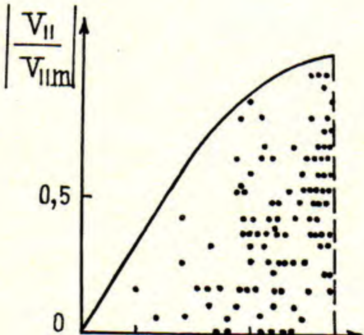
The unipolar sunspot SD 42/86 was observed on the Sayan observatory vector magnetograph on 25 August and from 30 August to 2 September 1986. The instrument, the observing technique and the treatment procedure are described in detail in [7]. The observations were carried out in line FeI λ5250 Å, with a 2x2" slit and the scanning rate of 2" s^{-1}. Simultaneously with measurements of all

Stokes parameters, the line-of-sight velocity signal from the line-of-sight velocity compensator was recorded. The time required for taking one magnetogram was 20-50 minutes. A total of 16 observation sequences were obtained.

3. Treatment results

Maps of the distribution of the longitudinal component of the magnetic field and of line-of-sight velocities show a negative correlation described in our earlier paper [2]. On 15 maps the $V_{\parallel}$-maximum lies on the zero line of $H_{\parallel}$ arising due to the projection or within 2-4" from it. On 30 August when the sunspot was located near the disk center, the usual picture of the Evershed effect was not observed, as well as the zero line of $H_{\parallel}$.

In addition to making a direct comparison, for each map we constructed the dependence of the modulus of line-of-sight velocity (normalized to maximum velocity $V_{\parallel m}$ on the map) on the value of the inclination angle (γ) of the magnetic field vector to the line of sight. In the case of parallelism of the field and the velocity, the largest $V_{\parallel}$ must correspond to the smallest γ. Fig. 1 (1 September, 1.02-1.21 UT) gives an example of such a dependence; a solid line corresponds to the function $\sin|\gamma|$.

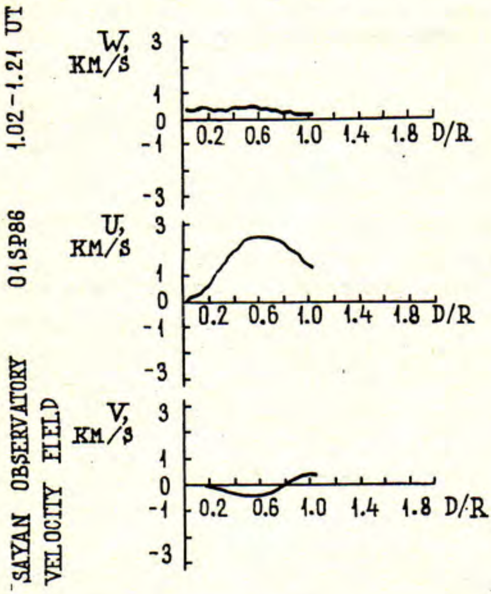


F i g. 1. The dependence of the value of line-of-sight velocity on the inclination angle of the magnetic field vector to the line of sight.

Maximum line-of-sight velocities in this case lie near large angles γ , i.e., in places where the magnetic field is nearly perpendicular to the line of sight, such a relationship between $V_{\parallel}$ and γ , as the negative correlation between $V_{\parallel}$ and $H_{\parallel}$, indicate, most likely, the orthogonality of the motion and the field rather than their parallelism.

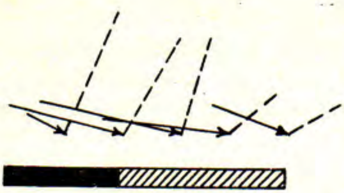
Further, the distribution of the velocity vector in sunspot radius was calculated for the 15 maps under the assumption of circular symmetry. The calculations used a method described in [2]. The possible inclination of the velocity field to the solar surface was neglected because, as mentioned above, at the disk center the Evershed effect in the sunspot disappeared.

The obtained distribution of three components of the velocity vector for the observation mentioned above is shown in Fig. 2.



F i g. 2. The components of the velocity vector in cylindrical symmetry.

The predominant motion in this sunspot is outflow (U is the radial velocity component), the maximum velocity of 2.5 km s^{-1} corresponds to D/R = 0.6 (D/R is the distance from the sunspot center in units of the sunspot radius), and downward velocities of about 0.3 - 0.4 km s^{-1} are observed throughout the sunspot (W is the vertical component). The tangential (V) component shows a complicated character of the rotation of material in the sunspot (a maximum value is 0.4 km s^{-1}, and "+" is the counter-clockwise rotation). Such a distribution of the velocity vector fits in well with that described earlier; however, attention should be paid to the fact that virtually throughout the sunspot penumbra the velocities of material are directed across magnetic field lines. This is clearly seen in Fig. 3, showing velocity vectors (arrows) and magnetic field



F i g. 3. Velocity vector projections and mean inclination angles of field lines.

lines (dashed lines) projected onto a plane perpendicular to the solar surface (for the same observation). The magnetic field vector was also determined from circular symmetry in $H_{\parallel}$.

The results described above, in our opinion, either speak for the lack of a frozen-in field to the plasma in a sunspot or require a different explanation, without rejecting the frozen-in condition. In search of an answer to this question, we tried to divide the magnetic field and velocities into two components such that one component make a larger contribution to the field signal, and the other contribute more strongly to the velocity signal.

4. Discussion

4.1. A two-component model of the sunspot penumbra magnetic field

Let us imagine that the magnetic field in the sunspot penumbra consists of two independent components: a dark one with a strong horizontal field and a light one with a more vertical magnetic field. Such components can be, for example, separate magnetic tubes. This supposition corresponds quite well to observations with high spatial resolution. In observations with low resolution signals from these two components will combine to give some resulting (averaged) signal:

$$\begin{Bmatrix} J \\ Q \\ U \\ V \end{Bmatrix} = A_d \begin{Bmatrix} J \\ Q \\ U \\ V \end{Bmatrix}_d + (1 - A_d) \begin{Bmatrix} J \\ Q \\ U \\ V \end{Bmatrix}_b , \qquad (1)$$

where J , Q , U , and V are the corresponding Stokes parameters, and A_d characterizes the contribution of the dark component (hereafter indices d and b correspond to the dark and bright components, respectively). The coefficient A_d is defined as:

$$A_d = (1-\alpha)\, I_d / ((1-\alpha) I_d + \alpha I_b) , \qquad (2)$$

where $I_{d,b}$ is the brightness of the components with respect to the photosphere, and α is the fraction of the averaged surface occupied by light elements.

Hence, on the basis of the measured (averaged) magnetic field, by specifying the field in the dark component, one can try to reconstruct the field in the light component.

As an example, we consider an idealized sunspot with a field varying as:

$$H(\rho) = H_0 \left(1 + \rho^2 + \rho^4 + \rho^8 + \rho^{16}\right)^{-1} , \qquad (3)$$

where H_0 is a maximum field strength, and ρ is the distance from the sunspot center in units of penumbra radius. The distribution of the inclination angle (δ) of the field vector to the vertical will be the same as in a paper of Wittman [8] (see Table 1, column

Table 1

ρ	H,G	δ^0	H_d,G	δ^0_d	H_b,G	δ^0_b
0.4	2445	59	2571	90	2100	44
0.5	2203	70	2317	90	2100	51
0.6	1925	78	2024	90	2000	68
0.7	1619	83	1703	90	1600	75
0.8	1291	87	1358	90	1300	85
0.9	941	89	990	90	800	90
1.0	580	90	610	90	500	90

3). According to data reported by Muller [9], we put $I_d = 0.52$, $I_b = 0.9$ for the inner penumbra and $I_d = 0.6$, $I_b = 0.95$ for the outer penumbra; $\alpha = 0.43$. We take H_0 for the averaged field to equal 2900 G. For the dark component we shall assume $H_0 = 3050$ G, with the same distribution (3) in ρ and the horizontal direction of the field (such a choice of H_0 for the dark element is caused by the desire to have the strength $H_d = 1700$ G for $\rho = 0.7$ for comparison with Abdusamatov's observations [10]). The above parameters fully describe the averaged field (H , δ) and the dark component field (H_d , δ_d) and permit the field of the bright component (H_b, δ_b) of the penumbra to be calculated from (1).

Using calibration curves calculated by Staude [11], from the given H and δ , and H_d and δ_d we determined the respective Stokes parameters $\begin{Bmatrix} J \\ Q \\ U \\ V \end{Bmatrix}$ and $\begin{Bmatrix} J \\ Q \\ U \\ V \end{Bmatrix}_d$. After that, formula (1) was used to determine $\begin{Bmatrix} J \\ Q \\ U \\ V \end{Bmatrix}_b$ and, finally, H_b and δ_b . Table 1 gives the results of this calculation.

The calculated magnetic field in the light elements satisfies quite well the observed characteristics. For example, the inclination angle of the vector to the vertical varies from 44° on the inner boundary of the penumbra to 90° on its outer boundary. The magnetic field strength in the light element is by 100-300 G smaller than that in the dark element. (According to an estimate made by Abdusamatov [10], this difference makes up 100-400 G). A change of the free parameter H_0 for the dark component causes only the value of H_b to vary but does almost not affect the angles δ_b .

4.2. <u>The velocity structure in the penumbra</u>

We shall now suppose that in the penumbra, along with magnetic field structures, there also exist two independent systems of motions: along dark and light elements, respectively. Of course, the inclusion of velocities in the model will also affect the preceding step: H_b and δ_b of the calculated field must change; however, since we are constructing only a qualitative model, such changes can be neglected in the first approximation.

It will be assumed that the mass motion out of the sunspot proceeds along the horizontal (dark) component of the magnetic field, and the velocity of such a motion is 4 km s^{-1} as a maximum and varies in the same fashion as the radial (v) component in Fig. 2. In light elements with a more vertical field the material descends with the velocity of 1 km s^{-1}. For such conditions, an averaged velocity field was calculated. The velocities were determined in the following way. First, a spectral line profile from the dark and light components was constructed, by taking their different weights into account. After having determined the residual intensity $r(\lambda)$, we calculated the integrals $\int_{\lambda_1}^{\lambda_2} r(\lambda)\, d\lambda$ in the red and blue wings of the line. The limits of integration corresponded to the exit slit edges of the Sayan observatory vector-magnetograph photometer ($\lambda_1 = 37\,\text{mÅ}$ - one edge of the slit, and $\lambda_2 =$

= 95 mÅ - the other edge of the slit from the center of the unshifted line). Subsequently, with stationary slits (limits of integration) the contour $r(\lambda)$ was displaced until the integrals in its wings became equal. Such a procedure of determining the velocity is similar to operation of a line-of-sight velocity compensator of the magnetograph. The results obtained by this method are given in Table 2. (The angular distance of the sunspot $\theta = 45°$,

Table 2

ρ	$V_{\parallel}$, km s^{-1}	γ° mean f.	ρ	$V_{\parallel}$, km s^{-1}	γ° mean f.
1.0	-0.51	45	0.4	1.21	-76
0.9	-0.82	44	0.5	1.48	-65
0.8	-1.05	42	0.6	1.41	-57
0.7	-1.14	38	0.7	1.30	-52
0.6	-1.18	33	0.8	1.11	-48
0.5	-1.08	25	0.9	0.82	-46
0.4	-0.76	14	1.0	0.51	-45

and Λ denotes the limb-ward side of the penumbra. The angles for a mean field are also presented. The positive velocity corresponds to the motion from the observer). For the above case it is evident that large velocities lie within the range of larger angles γ. On the whole, the $V_{\parallel}$-distribution corresponds to the observed averaged picture of the Evershed effect.

Let us examine how the picture of the V -distribution will vary with a change in angular distance θ of the sunspot from the disk center. Fig. 4 presents the dependences of $|V_{\parallel}/V_{\parallel m}|$ on $|\gamma|$

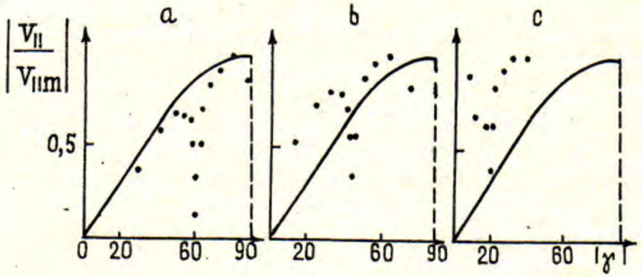


Fig. 4. The dependence of line-of-sight velocity on the modulus of angle $|\gamma|$ for different angular positions of the sunspot.

for three values of the angles θ. For $\theta = 30°$ (Fig. 4a), this dependence corresponds quite well to orthogonality of the motion and the field; with increasing θ ($\theta = 45°$, Fig. 4b) the apparent orthogonality begins to be violated and, for large angular distances ($\theta = 70°$, Fig. 4c), changes to parallelism of the field and the velocity. Kotov's observations [1] just correspond to the last case ($\theta = 66°$), while our observations fall within the range $\theta < 50°$.

The model of motions in a sunspot considered above explains also another peculiarity in the Evershed effect, namely the "flags" observed by Prof. V.Bumba. Indeed, when averaging two velocity fields with different relationships between them the resulting line profile will show either asymmetry or will even split into two profiles: an almost unshifted line and a strongly shifted weak satellite. This is quite discernible if the line profile is examined at different angular distances of the sunspot from the disk center.

Hence, the model of a two-component structure of the penumbra agrees nicely with observed distributions of the magnetic field and the velocity in a sunspot and can explain some contradictions associated with the view that the field is frozen-in to the plasma in a sunspot.

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