Connection between the appearance of a filament and changes in the magnetic field of an active region

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The dynamic behavior of the distribution of the longitudinal magnetic field gradient in the close vicinity of the line of separation of polarities is studied. It is shown that a necessary condition for the appearance of a filament within an active region is a shift in the grad $H_{\parallel}$ distribution toward lower values of the gradient and uniformity of the line of separation of polarities with respect to the magnetic field, and the maximum values of grad $H_{\parallel}$ must not exceed a certain limiting value.

1. INTRODUCTION

The dependence of the formation and stability of filaments on the configuration of the supporting magnetic field is an important problem of the physics of solar prominences. Whereas much is already clear at the qualitative level, the problem of establishing a quantitative expression for this dependence still remains open. The choice of the parameters characterizing the magnetic field configuration plays an important role here.

In Ref. 1 it was shown that cases of the existence of a filament within an active region correspond to certain values of the horizontal gradient of the longitudinal magnetic field (grad $H_{\parallel}$) in the close vicinity of the line of separation of polarities (LSP). In the present paper we attempt a quantitative description of the dependence of the appearance of filaments on the variation of the distribution of grad $H_{\parallel}$ along the LSP.

2. OBSERVATIONAL MATERIAL AND TREATMENT METHOD

Magnetograms of the longitudinal magnetic field and Hα filtergrams served as the material for the research. The magnetograms were obtained on the panoramic magnetograph of Sayan Observatory in the Fe I λ 5250 Å line. The observations were made on September 1-4 and 7, 1978. The time resolution of the magnetographic material used was one day and the spatial resolution was 1".8 × 3".6.

The filtergrams at the center of the Hα line were obtained on the ATsU-5 horizontal solar telescope of Sayan Observatory. In addition, we drew upon daily Hα filtergrams of the complete solar disk of other observatories obtained on September 1-7 in the Solar Service program. The spatial resolution of the filtergrams was 2-3".

For the analysis we chose material pertaining to a complex of two closely spaced active regions, where the formation of filaments was observed in the investigated period. Both active regions were recorded as No. 243 in the Solnechnye Dannye bulletin.[2]

By the time of the start of the observations, the eastern active region AR 1 was near the maximum of its development. It broke up during the period of the observations, and by September 7 only the leading sunspot with a penumbra remained of the group of sunspots. The most rapid breakup occurred from September 2 to 4. During this time the magnetic flux of AR 1 decreased by a third.[3] The western active region AR 2 developed on September 1 at a distance of ∿3° from AR 1 in an old magnetic field of the leading polarity (in accordance with Hale's law, the leading polarity in this cycle was the north polarity). Intensive growth of the magnetic flux of AR 2 occurred from September 1 to 3, and by September 4 the region reached maximum development. On September 1-7 the trailing part of AR 2 was immediately adjacent to the leading part of AR 1.

Seven lines of separation of polarities can be distinguished on magnetograms of the longitudinal field of the activity complex (Fig. 1). The LSP boundaries varied from day to day, which is connected mainly with the evolution of the magnetic field.

The LSP I-IV existed for the entire observed period, LSP V was reliably recorded on September 1-4, while LSP VI was recorded only on September 1 and 2. A dark formation with a width of ∿ 4-5" and a length of ∿ 20", lying on a line of separation of polarities, and existing for more than a day was considered as a filament. The formation and development of filaments was observed on LSP I and LSP IV.

As was done in Ref. 1, we chose the quantity grad $H_{\parallel}$ in the closest vicinity of the filament as a characteristic of the magnetic field. Although the measured gradients may not pertain to the field lines directly supporting the filament, as a whole they still characterize the magnetic field configuration in which the filament is formed.

To determine grad $H_{\parallel}$ we used maps of $H_{\parallel}$ with isolines of ± 30, ± 60, ± 90, ± 120, and ± 200 G. Lines, along which the distance between the + 30 and − 30 G isolines was measured, were drawn perpendicular to the LSP at approximately equal intervals (∿ 4"). In those cases when this distance was less than an element of spatial resolution of the magnetograph, we used lines with higher absolute values of the magnetic field. Small hills of the magnetic field (with sizes of less than 8-10") were neglected in determining the gradients.

The $H_{\parallel}$ gradients were determined for the period of September 2-4, since on September 1 and 7 the activity complex was located at distances exceeding 35° from the central meridian, which could entail a strong influence of projection effects on the measurements. For LSP IV the gradients were determined only on September 2, since this line was absent on subsequent days. In the case of LSP VII it proved impossible to determine the gradients by the method

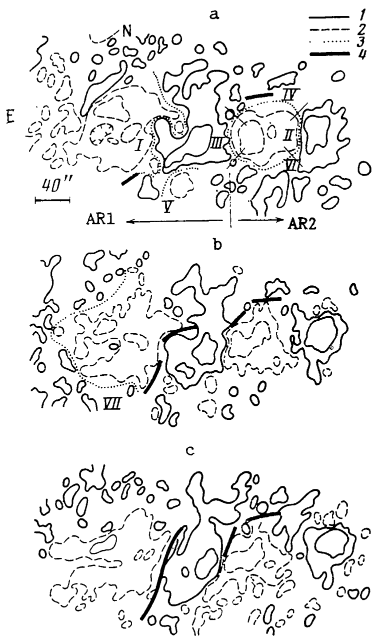

FIG. 1. Maps of the longitudinal magnetic field: a) at 03^h02^m UT on Sept. 2, 1978; b) 03^h42^m UT on Sept. 3, 1978; c) 01^h38^m UT on September 4, 1978. Only isolines of ± 30 and ± 120 G are plotted. The numbers of the LSP from Table I are denoted by Roman numerals and the LSP boundaries are marked by thin straight lines. 1) Leading polarity; 2) trailing polarity; 3) lines of separation of polarities; 4) positions of filaments.

described because of the great irregularity of the structure of the old magnetic field. We also note that LSP VII was not drawn in Fig. 1a, since a spurious reversal of magnetic field polarity, due to the projection effect, was recorded to the north of AR 1 on September 2.

3. RESULTS

The results of the treatment of the magnetograms are given in Fig. 2 in the form of histograms of the distribution of grad $H_\parallel$ separately for each investigated LSP (data are given only for LSP I-III) and for each day of observations. In Table I we give certain parameters characterizing the distribution of grad $H_\parallel$ on the LSP: the average value of the gradient, $\langle$grad $H_\parallel\rangle$, and the maximum value δ of the gradient (below we shall call it the width of the distribution).

Let us consider the time behavior of the parameters of the grad $H_\parallel$ distribution for individual LSP and its connection with the appearance or absence of a filament.

On September 2, LSP I was characterized by a rather large width δ = 0.0772 G/km and $\langle$grad $H_\parallel\rangle$ = 0.0219 G/km. At its south end there was a small section (three profiles) with the parameters δ = 0.0046 G/km and $\langle$grad $H_\parallel\rangle$ = 0.0042 G/km on which a filament ∿ 20" long was observed on September 1 and 2. On September 3 the appearance of the grad $H_\parallel$ distribution changed considerably. The entire histogram shifted toward smaller gradients, while the width of the distribution decreased considerably: $\langle$grad $H_\parallel\rangle$ = 0.0115 G/km, δ = 0.0248 G/km (the magnetogram was obtained at 03:42 UT). At 01:25 UT on this day, the filament that existed earlier on the south section of the LSP had about the same size as on the previous day. In addition, a new filament with a length of ∿ 20" appeared on the north section of the LSP. Five hours later, the lengths of both filaments had increased about twofold, mainly by the "advance" of the filaments toward each other along the LSP. The position of the filaments at the time 06:12 UT is shown in Fig. 1b. The filaments were separated by a section with $\langle$grad $H_\parallel\rangle$ = 0.0139 G/km, whereas for the sections with filament, $\langle$grad $H_\parallel\rangle$ = 0.0085 G/km. The shift in the grad $H_\parallel$ distribution toward small gradients and the decrease in the width of the distribution also continued on September 4. On this day the two filaments joined, and the length of the filament was now ∿ 70% of the length of the LSP. The filament continued to exist on succeeding days (September 5-7), although its position and shape changed somewhat.

Let us further consider the lines of separation of polarities adjacent to AR 1. LSP V had a small length, about a fourth as long as LSP I. The values of $\langle$grad $H_\parallel\rangle$ were close in magnitude to the average gradients for LSP I on September 3 and 4, while the value of δ was only a little higher. The characteristic form of the distribution on all three days when measurements were made is a sharp maxi-

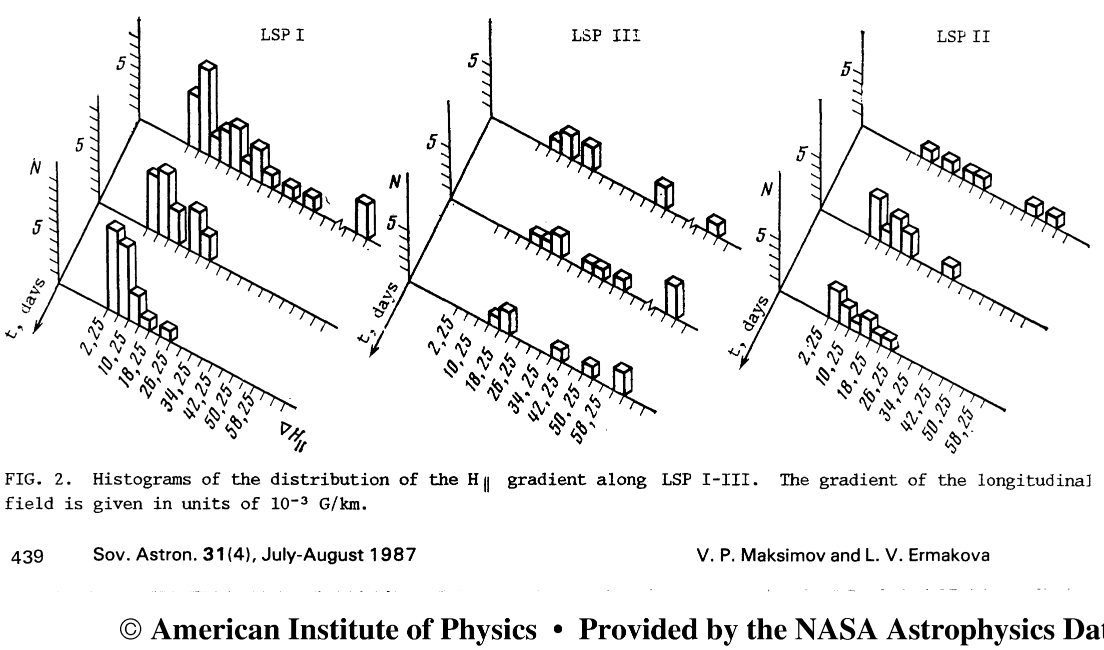

FIG. 2. Histograms of the distribution of the $H_\parallel$ gradient along LSP I-III. The gradient of the longitudinal field is given in units of 10^{-3} G/km.

TABLE I

LSP No.	Date	⟨grad $H_\parallel$⟩	δ	α	Ratio of filament length to LSP length,%
		G/km			
I	2.IV.1978	0.0219	0.0772	0.78	10
	3	0.0115	0.0248	0.36	50
	4	0.0082	0.0231	0.12	68
II	2	0.0305	0.0579	0.93	0
	3	0.0111	0.0309	0.21	0
	4	0.0110	0.0193	0.50	0
III	2	0.0289	0.0965	1.17	0
	3	0.0501	0.0964	1.18	0
	4	0.0331	0.0579	0.71	0
IV	2	0.0030	0.0033	0.00	75
	3	0.0048	0.0083	0.28	86
	4	0.0052	0.0105	0.40	67
V	2	0.0120	0.0231	0.20	0
	3	0.0098	0.0158	0.20	0
	4	0.0140	0.0347	0.38	0

mum, about in the middle of the LSP. A filament was not observed on LSP V in the period from September 1 to 7.

The parameters of the grad $H_\parallel$ distribution on LSP III were characterized by considerably higher values than for LSP I. A filament was not observed on this LSP.

Let us proceed to a discussion of the lines of separation of polarities connected with AR 2. On LSP IV the widths of the distribution and the average gradients of the longitudinal magnetic field were small during the entire investigated period (see Table I). A filament with a length of ∿ 35" initially appeared on September 2 on the west part of the LSP. On September 3 the length of this filament increased, while a new filament with a length of ∿ 30" appeared on the east part. By September 5 the filaments looked like a single unit. A certain decrease in the ratio of the length of the filament to the length of the LSP is due to the more rapid increase in the length of the LSP in comparison with the increase in the length of the section occupied by filament. It should be noted that the east end of the filament, as in the case of the development of the filament on LSP I, "stopped" in the region of high gradients of the longitudinal magnetic field.

And finally, let us consider the behavior of the parameters of the grad $H_\parallel$ distribution along the line of separation of polarities in the young active region (LSP II). On September 2 the values of both parameters were high, but by September 4 they had decreased considerably and become close to those of the parameters of the grad $H_\parallel$ distribution on LSP I. However, a filament did not appear on LSP II either on this or on subsequent days. And only on September 6 and 7 was the penetration of the west end of the filament lying on LSP IV into AR 2, now along LSP II, observed.

4. DISCUSSION OF THE RESULTS

As we did in Ref. 1, we calculated the medians of the gradient of the longitudinal magnetic field on sections of LSP with and without a filament. On sections with a filament (45 profiles), grad $H_\parallel$ = 0.0072 G/km, while on sections without a filament (126 profiles), grad $H_\parallel$ = 0.0202 G/km. The maximum measured gradient on a section of LSP with an existing filament was 0.0231 G/km. The corresponding values determined in Ref. 1 were 0.0074, 0.0222, and 0.0276 G/km. The agreement could be called good, but one must allow for the fact that in Ref. 1 the results were obtained for the Fe I λ 5253 Å line, which in the present paper they were obtained for the Fe I λ 5250 Å line. Although there are reasons to assume that measurements of the longitudinal magnetic field based on these two lines should not differ significantly,[4,5] we shall not discuss this question in the present paper. The main thing of importance for us here is that the grad $H_\parallel$ distributions on sections with and without a filament are shifted relative to each other and a limiting value of grad $H_\parallel$ exists, upon exceeding which a filament does not appear. In addition, the histograms themselves are qualitatively similar (Fig. 3).

Thus, the form of the histograms of the grad $H_\parallel$ distribution along an LSP and its temporal evolution allow one to judge the probability of the appearance of a filament on the given LSP or individual sections of it.

The histograms do not, however, reflect the fact that the maximum value of grad $H_\parallel$ may occur at the ends of an LSP or that the distance between adjacent maxima is so great that rather extended sections with low values of grad $H_\parallel$ may exist between them, and hence a filament may appear on these sections. This fact explains Fig. 4, where we give values of grad $H_\parallel$ measured successively along LSP I, II, and III. For simplicity, an LSP was drawn out into a straight line and the distances between profiles were assumed to be the same. Since because of changes in the length and position of the LSP, we could not identify one and the same profile on different days of observations, one end of the LSP was taken as the origin. Therefore, it is expedient to attempt to introduce a certain numerical parameter that would characterize the nonuniformity of the grad $H_\parallel$ distribution along an LSP:

$$\alpha = \frac{\sum_{i=1}^{k} \beta_i}{n}.$$

Here n is the number of measurements (profiles) of grad $H_\parallel$, k is the number of extrema on a smoothed graph of values of grad $H_\parallel$ (Fig. 4), and β_i is the weight coefficient of the i-th maximum, defined as

$$\beta_i = \begin{cases} 1 & \text{for } \operatorname{grad} H_{\parallel i} \leqslant \operatorname{grad} H_\parallel^{\max}, \\ \dfrac{\operatorname{grad} H_{\parallel i}}{\operatorname{grad} H_\parallel^{\max}} & \text{for } \operatorname{grad} H_{\parallel i} > \operatorname{grad} H_\parallel^{\max}, \end{cases}$$

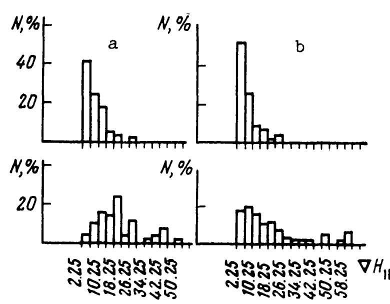

FIG. 3. Histograms of the distribution of the $H_\parallel$ gradient for cases of the presence and absence of a filament. a) For active regions SD 312/82 and 322/82; b) for active region SD 243/78. ∇H is in units of 10^{-3} G/km.

where grad $H_{\parallel}$max is the maximum value of grad $H_{\parallel}$ measured on a section of LSP with an existing filament (0.0231 G/km in our case). All the minima on a graph were taken with a weight of one. The calculated values of the parameter α are given in Table I.

From Table I it is seen that the parameter α of nonuniformity of an LSP with respect to the gradient of the longitudinal magnetic field describes the situation on LSP I, III, and IV rather well: Low values of α correspond to the existence of a filament (LSP I and IV) and, vice versa, high values of α characterize the absence of a filament (LSP III). The situation on LSP V is poorly described. Here the values of α are favorable for the appearance of a filament, but one did not appear in all the days of observations. This contradiction is explained by the fact that the length of this LSP was very small (four to five profiles), while the gradient distribution along it had the form of a single sharp maximum, in which δ equaled grad $H_{\parallel}$max = 0.0231 G/km on September 2, while it exceeded this by a factor of 1.5 on September 4.

The situation on LSP II is more complicated. On September 3, and especially on September 4, the supporting magnetic field in the vicinity of this LSP was favorable for the appearance of a filament, not only with respect to the parameter α but also <grad $H_{\parallel}$> and δ. Nevertheless, a filament did not appear on these days. This contradiction evidently reflects a circumstance that was emphasized earlier in Ref. 1: The presence of sufficiently extended sections with low values of grad $H_{\parallel}$ on an LSP is a necessary but not a sufficient condition for the formation of a filament. The reason for this may consist in the fact that the parameter α cannot adequately describe the properties of the magnetic field at the altitudes where a filament is formed (for example, the "flattening" of the tops of arches in Pikel'ner's model[4]). An investigation of the characteristics of LSP from images of an active region in x-ray and radio emission may prove useful here. It is also possible that this can be allowed for indirectly by introducing a parameter describing the age of the active region, but additional research is required for this.

Thus, our investigations allows us to draw the following conclusions.

1. The magnitude of the supporting magnetic field plays an essential role in the process of the appearance and the existence of a filament within an active region.

2. An important characteristic of the supporting magnetic field, which can be determined from observations with a moderately high spatial resolution, is the grad $H_{\parallel}$ distribution in the immediate vicinity of the line of separation of polarities: If the grad $H_{\parallel}$ distribution along the line of separation of polarities is not shifted toward low values of the gradient (<grad $H_{\parallel}$> is large) and the LSP is highly nonuniform in magnetic field with maxima exceeding a certain limiting value of the gradient (α is large), then a filament does not appear on this LSP. The opposite statement requires additional research.

These conclusions are important for an understanding of the physical processes lying at the basis of the formation and stability of solar prominences. In addition, they are of interest in the analysis of preflare situations, in which the activation of a filament plays a definite role, since data on the magnetic field in the active region are often unavailable in these cases. The presence of a filament enables one to judge the average and maximum values of the gradient of the longitudinal magnetic field in the closest vicinity of the line of separation of polarities.

In conclusion, we note that the results of Ref. 1 and the present paper and the procedure of construction and analysis of the distribution of gradients of the longitudinal magnetic field in the closest vicinity of the line of separation of polarities lying at their foundation can also be of value for quiescent filaments outside of active regions. This is indicated by the agreement between our results and those of a recently published qualitative investigation of the connection between the positions of filaments and large-scale magnetic fields.[7]

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Note added in proof. The equation given for the parameter α does not allow for the influence of the ends of the LSP, at which the conditions for the existence of filaments cease to be satisfied in general. To allow for this influence, we introduce the coefficient γ:

$$\alpha = \frac{\sum_{i=1}^{k} \beta_i + 2\gamma}{n+2}.$$

Assigning the value one to γ, we recalculated the values of α for all the LSP. For extended LSP these

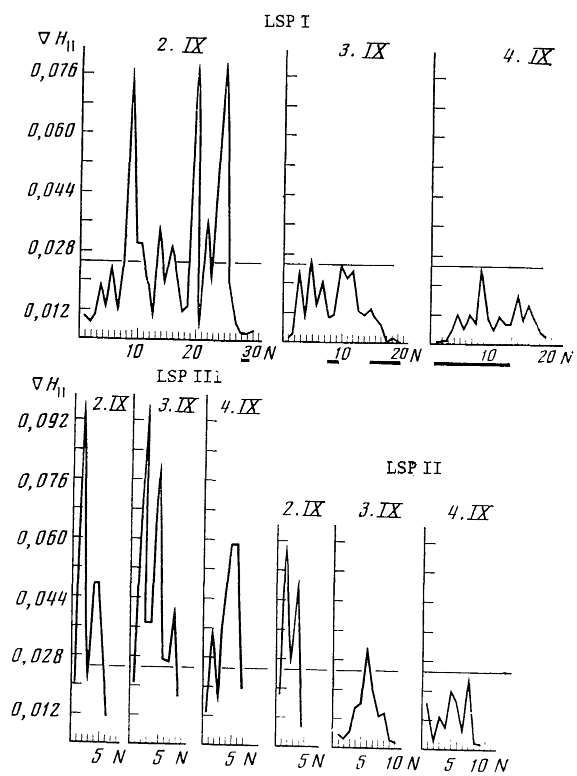

FIG. 4. Behavior of grad $H_{\parallel}$ on LSP I-III. The positions of filaments are marked by a heavy line underneath.