

**EVOLUTION OF MAGNETIC FIELDS AND CHROMOSPHERIC STRUCTURES IN SOLAR FLARE ON JUNE 26, 1981**

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ABSTRACT

The solar 1B-flare of 26 June 1981 was analysed using the observational data obtained with the Echelle spectrograph of Kyiv University Observatory, as well as the white light and H-alpha telescopes of Debrecen Observatory. To diagnose the small-scale magnetic fields in the flare at the photospheric level, the FeI 6301.5/6302.5 magnetic line ratio was applied. Evidences were found for the magnetic field strengthening during the flare. This effect was observed at the peak of the flare both for magnetic flux and field strength modulus measured from Stokes V peak separations of FeI 6301.5 and 6302.5 lines. A moderate positive correlation was found between magnetic field values and H-alpha brightnesses at the same places. Characteristics of the H-alpha structures at the chromosphere as well as proper motions of sunspots are measured to determine the changes in the magnetic field topology.

1. INTRODUCTION

The transformation of the magnetic field during a flare is one of the unsolved problems of solar physics. It is obvious at present that only magnetic energy can provide different forms of flare energy (e.g. Heyvaerts et al. 1977, Somov & Syrovatskij 1979). On the other hand, even the basic effect of magnetic energy reduction during the flare has not been recorded in all flares. In particular, for weak flares the magnetic field changes do not often differ from the evolution of the active region (Ribes 1969, Rust 1976). Magnetic field measurements of the 3B/X5.7 flare in the infrared MgI 12.3  $\mu\text{m}$  line using a Fourier spectrometer also did not reveal any significant changes of the magnetic field strength (Deming et al. 1990). To the contrary, magnetic field diagnostics in FeI 5247.1 and 5250.2  $\text{\AA}$  lines have convincingly shown an amplification of the magnetic field in the peak of the 2B flare (Lozitska & Lozitskij 1994).

Koval' and Stepanjan (1972) have used two spectral lines, FeI 6302.5 and CaI 6102.7  $\text{\AA}$ , with different heights of formation in the atmosphere and discovered that the field strengths in higher layers predominate over those in lower ones. This strange effect, perhaps connected with the non-potential field structure, was observed only in sunspots not far from the flare. For remote sunspots the relevant magnetic field strengths were practically equal. But an analogous effect of field predominance was also

measured outside flares, in particular, in pores, surges and 'moustaches' (i.e. Ellerman's bombs). This means that non-potential field structure can arise not only in flares but also in non-flare features.

We have studied a 1B-flare using a technique similar to the line ratio method reported by Stenflo (1973) which allows to determine some characteristics of spatially unresolved magnetic structures. The main idea was described earlier in detail by Lozitska and Lozitskij (1994) for the case of spectral lines FeI 5247 and 5250  $\text{\AA}$ . In the present paper we use another pair of lines: FeI 6301.5 and 6302.5  $\text{\AA}$ , which are formed 40-60 km higher than the pair FeI 5247/5250 and they have a lower temperature sensitivity.

2. OBSERVATIONAL DATA

The Hale Region 17705 was observed in the Debrecen Observatory and at its Gyula Observing Station with the white-light and H $\alpha$  telescopes on June 26 1981. The white-light full-disk observations were obtained with the photoheliographs of 13 and 15 cm objective diameters on 14x14 films. The diameter of the disc is about 10.5 cm. This material contains 24 plates between 4:35 and 15:04 UT. Debrecen's white light heliograms and the method of data reduction allows us to measure the positions of spots with a precision of 0.1 heliographic degrees. (For the details of the observational method and data reduction see Bumba et al. 1993)

The H $\alpha$  filtergrams were obtained with a 53-cm coronagraph through a 0.5  $\text{\AA}$  passband H $\alpha$  filter on 38 mm films. The diameter of the disc is about 12.5 cm. These telescopes can record the solar images with a spatial resolution of about one arc second but at least of two arc seconds with exposures of about 1/60 sec. The H $\alpha$  filter is tunable, the observations were recorded at  $\Delta\lambda=0, \pm 0.5 \text{\AA}, \pm 1.0 \text{\AA}$ .

The spectral data were obtained with the Echelle spectrograph of the horizontal solar telescope of the Kyiv University Astronomical Observatory (Kurochka et al., 1980). This spectrograph can record the solar spectrum simultaneously from 3800 to 6600  $\text{\AA}$  with a spectral resolution of nearly 200000 in the green region and with a temporal resolution of about several seconds. The spectra have been recorded on ORWO WP1 and WP3 plates with a temporal resolution of 2.5-10 s. A microphotometer M $\Phi$ -4 was used to scan the spectrograms.

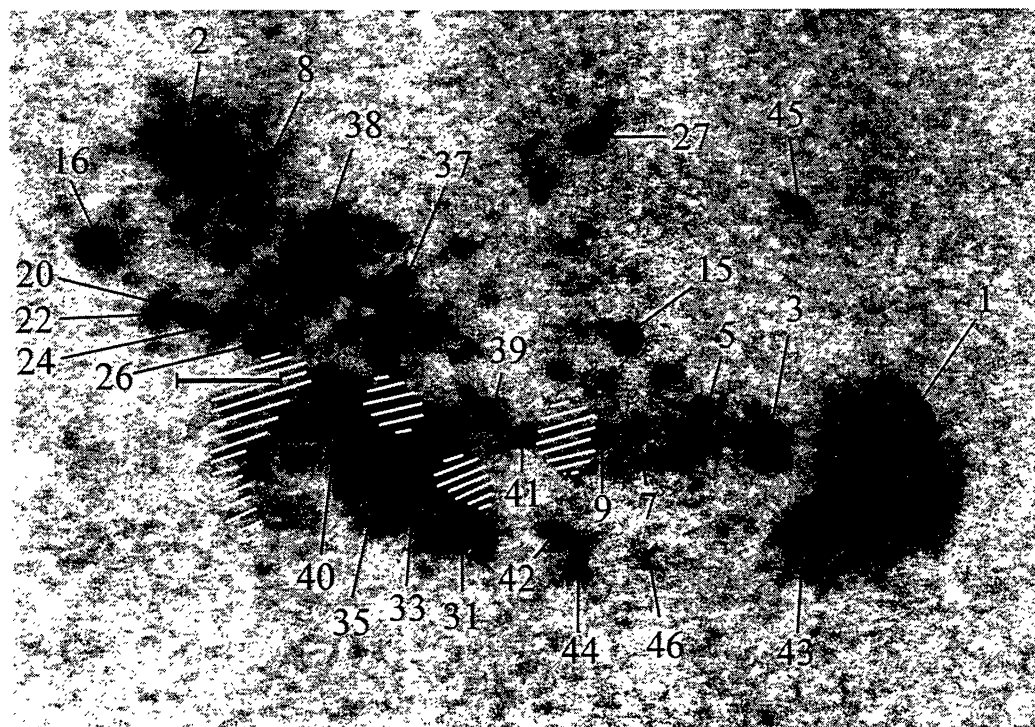
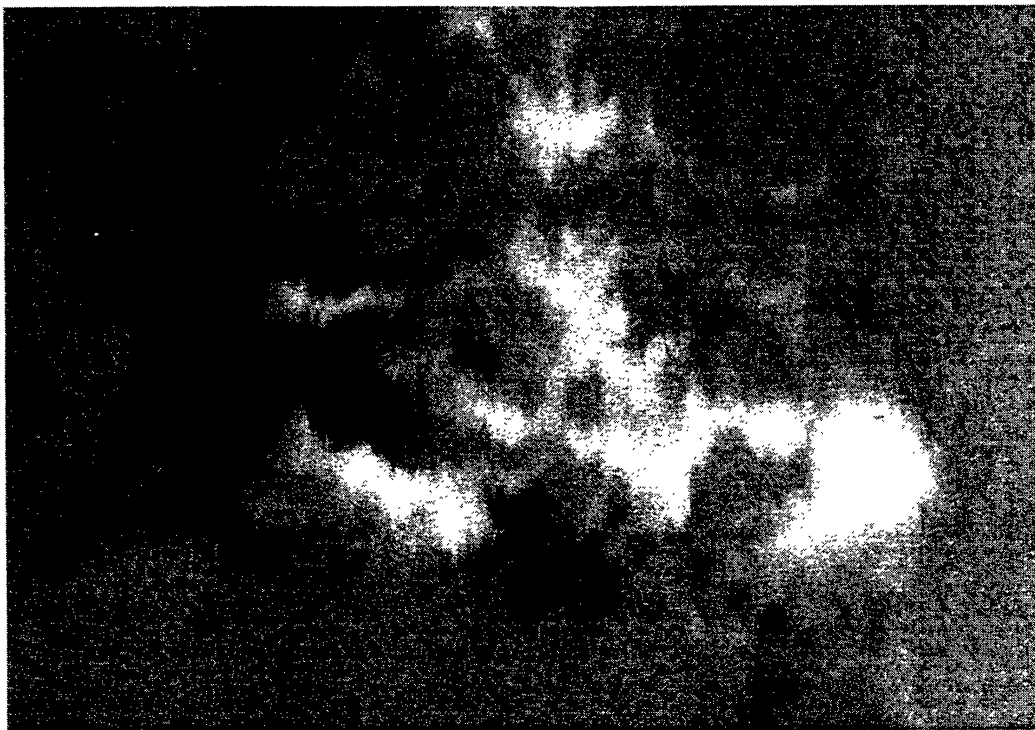


Figure 1. Hale region 17705 observed with the Kitt Peak magnetograph (above) and in white light (below). Lines indicate the sunspots by our numbering (see Text). A short interval below Spot No.26 indicates the place of the enter slit of the Echelle spectrograph. White hatched areas show the positions of the  $H\alpha$  flare knots.

## 2.1. Evolution of the HR 17705 in the Photosphere

The studied active region rotated onto the disk on 19 June 1981 at about N13. It was a developing large bipolar group and this simple structure still characterized the group on June 22 although several umbrae of opposite polarities got into the same large penumbra. On June 23 the Kitt Peak magnetogram shows that the central part of the group consists of the developing long peninsulas intruding into the the opposite polarities. In the N-S direction this means the alternating negative-positive-negative-positive polarities in this region. This structure of mixed polarities may have contributed to the fact that there were three times more flares on this day than on the previous day (on the basis of Solar-Geophysical Data). The peak of the flare activity was on June 24 when 5 flares of 1 importance and 8 subflares were observed in this region. After this day the activity was decreasing in the expanding and decaying group but several flares of 1 importance could be observed on June 25 and 26.

Figure 1 shows the AR under study in white light (6:15 UT) and also the magnetic map of Kitt Peak Observatory (15:04 UT) on June 26. One can see the developed active region with many small spots and pores as well as a complicated distribution of magnetic polarities. Some of these spots are marked with numbers on Figure 1. Odd and even numbers refer to positive and negative polarities respectively. Positive (preceding) and negative (following) polarities were mixed mainly in the central part of the group, where there were five large and several small umbrae with opposite polarities in one penumbra. Besides, spots of negative polarity (42, 44, 46) had arisen not far from the largest leader spot of positive polarity between spots 31 and 1. The visual inspection of the Kitt Peak magnetogram revealed that a process of mutual polarity mixing became stronger to the day of the studied flare. The brightest knots (white-hatched areas) of the flare arisen at the positions of highest horizontal gradient of the longitudinal magnetic field.

## 2.2. Development of the Flare on H $\alpha$ Filtergrams

The flare started at about 5:30 UT, reached its peak at 6:50 and was practically finished at 8:00. Conspicuous flare emission in the wing at  $\Delta\lambda = -1.0\text{\AA}$  was only visible by the flare peak, although small scale kernels connected with short Ellerman's bombs kept arising practically during the entire flare. We have observed at least 30 bombs from 5:28 to 8:19. One of these bombs at 6:42 marked the start of the bright flare knot which was observed with the Echelle spectrograph. The visible emission in the wing persisted until about 7:10 in this flare knot.

It is remarkable by visual inspection of the H $\alpha$  film that the flare didn't have a flash phase. This conclusion is also confirmed by the spectral observations of the Kyiv's Echelle spectrograph, which indicate that the H $\alpha$  line had only narrow ( $\leq 2\text{\AA}$ ) emission wings in all phases of the flare including the pre-peak phase. The maximum intensity of the H $\alpha$  emission was about 1.0 with respect to the continuum level at the moment of the peak (see also Figure 3 below).

## 2.3. Spectral Observations

Seven Zeeman spectrograms were obtained using circular polarization analyzer. All spectrograms refer to the same position on the Sun marked on Figure 1 by a short line. For all spectrograms the entrance slit of the Echelle spectrograph was crossing the position of a bright flare knot out of sunspots in an area of S-polarity magnetic field.

Two spectral lines of the FeI-816 multiplet were used for magnetic field measurements. For the first of them the wavelength is  $6301.515\text{\AA}$ , the  $EP$  is  $3.64eV$  and the height of formation is  $286km$ . For the second line the wavelength is  $6302.507\text{\AA}$ , the  $EP$  is  $3.67eV$  and the height of formation is  $264km$  (Gurtovenko & Kostik 1989). There are available Landé factors  $g_{eff}$  for both lines determined in laboratory (Zemanek & Stefanov 1976) which is important for reliable measurements due to the problem of the empirical Landé factors (Stenflo et al. 1984). Its value is 1.669 for the first line and 2.487 is for the second one. Both lines are formed practically at the same height in the atmosphere, but they have rather different magnetic sensitivities. For this reason, these lines are suitable for small scale magnetic field diagnostics (Lozitskij et al. 1992).

## 3. MAGNETIC FIELD DIAGNOSTIC

While studying the magnetic fields out of sunspots it was taken into account that the real structure is subtelesopic (unresolved) and it consisted of small scale magnetic fluxtubes of strong fields and of areas of weaker fields between them (see e.g. Stenflo 1973, Lozitsky 1980, Lozitskij 1986). Then the observed line profile  $I_o(\lambda)$  related to observed local continuum,  $I_{co}$ , can be obtained via the formula (Koutchmy & Stellmacher 1978)

$$\frac{I_o(\lambda)}{I_{co}} = (1-S)\left[\alpha \frac{I_{cf}}{I_{co}} \frac{I_f(\lambda)}{I_{cf}} + (1-\alpha) \frac{I_{cb}}{I_{co}} \frac{I_b(\lambda)}{I_{cb}}\right] + S \frac{I_{cs}}{I_{co}} \frac{I_s(\lambda)}{I_{cs}} \quad (1)$$

where  $S$  is the portion of scattered light,  $\alpha$  is the filling factor of magnetic fluxtubes,  $I_f(\lambda)$  and  $I_{cf}$  are the true line profiles and continuum intensities in the fluxtubes,  $I_b(\lambda)$  and  $I_{cb}$  are the same features for the background field, and  $I_s(\lambda)$  and  $I_{cs}$  are analogous parameters for the scattered light.

For the Stokes V parameter the same equation is valid if we replace the  $I_o(\lambda)$ ,  $I_f(\lambda)$ ,  $I_b(\lambda)$ ,  $I_s(\lambda)$  parameters with the  $V_o(\lambda)$ ,  $V_f(\lambda)$ ,  $V_b(\lambda)$ ,  $V_s(\lambda)$  parameters.

We can assume  $S \approx 0$ , because the investigated region was in the photosphere. Moreover, as a first approximation we can assume that the 'background' field contains practically a non-magnetic ( $B \approx 0$ ) plasma. In this case  $V_b(\lambda) \approx 0$ , and we can write

$$\frac{I_o(\lambda)}{I_{co}} \approx \alpha \frac{I_{cf}}{I_{co}} \frac{I_f(\lambda)}{I_{cf}} + (1-\alpha) \frac{I_{cb}}{I_{co}} \frac{I_b(\lambda)}{I_{cb}} \quad (2)$$



and

$$\frac{V_o(\lambda)}{I_{co}} \approx \alpha \frac{I_{cf}}{I_{co}} \frac{V_f(\lambda)}{I_{cf}} \quad (3)$$

It follows from the formula (3) that the observed Stokes V profile,  $V_o(\lambda)/I_{co}$ , differs from the true profile  $V_f(\lambda)/I_{cf}$  by the coefficient  $\alpha(I_{cf}/I_{co})$  which is one of unsolved problems of small scale magnetic field diagnostics. There is no appropriate method at present for its direct determination. However, if we use two spectral lines of the same multiplet which are formed at the same level in the atmosphere, then the resulting line ratio does not depend on the above mentioned coefficient. In this case we cannot determine the filling factor  $\alpha$ , but we could measure the magnetic field in the fluxtubes, as was described in detail by Lozitska and Lozitskij (1994).

For small scale magnetic field diagnostics, the most important characteristics is the Stokes V peak separation,  $\Delta\lambda_V$  (Stenflo et al. 1987, Lozitska & Lozitskij 1994). If the magnetic field is really weak, we can expect that

$$V(\lambda) \sim \frac{dI(\lambda)}{d\lambda} \Delta\lambda_H \quad (4)$$

where  $dI(\lambda)/d\lambda$  is the gradient of intensity in line profile and  $\Delta\lambda_H$  is the Zeeman splitting ( $\Delta\lambda_H = 4.67 \times 10^{-13} g \lambda^2 B$ , where the unit of  $\Delta\lambda_H$  and  $\lambda$  is  $\text{\AA}$  and that of  $B$  is Gauss).

Calculations show (see e.g. Lozitska & Lozitskij 1994) that for a line like FeI 5250 or 6302.5 the parameter  $\Delta\lambda_V$  is independent from the value of  $\Delta\lambda_H$  if  $\Delta\lambda_H/\Delta\lambda_D < 1$ , where  $\Delta\lambda_D$  is the Doppler half width. This means that we cannot expect any changes of  $\Delta\lambda_V$  if the field strength is not higher than about 1 kG. More precisely, one can observe any differences in  $\Delta\lambda_V$  from place to place which probably implies changes in thermodynamical conditions. However, if we determine the above mentioned line ratio, it should be unchanged (Stenflo et al. 1987).

The longitudinal magnetic field strength averaged over the aperture  $B_{\parallel}$  can be measured as the relative shift of the centers of gravity of the  $I + V$  and  $I - V$  profiles and equals

$$B_{\parallel} = \int_{\lambda_1}^{\lambda_2} \lambda V d\lambda / (4.67^{-13} g \lambda^2 \int_{\lambda_1}^{\lambda_2} I d\lambda) \quad (5)$$

where  $B_{\parallel}$  is expressed in G and  $\lambda$  in  $\text{\AA}$ .

The physical meaning of this parameter is similar to the longitudinal magnetic flux, in particular when lines with a small Landé factor and low temperature sensitivity are used. If the magnetic flux is intermittent in the form of flux tubes with field strength  $B$  and filling factor  $\alpha$ , then

$$B_{\parallel} \approx \alpha (I_{cf}/I_{co}) B \cos \gamma \quad (6)$$

where  $\gamma$  is the angle between the field line and the line of sight. One can use the well known formula

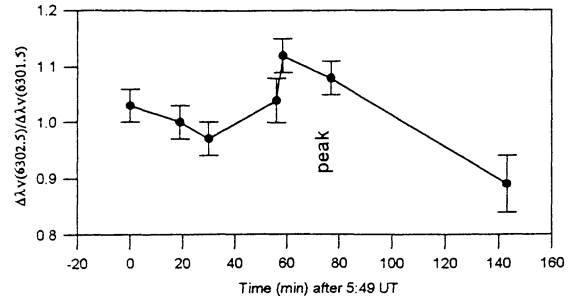


Figure 2. Observed changes of the line ratio  $\Delta\lambda_V(6302.5)/\Delta\lambda_V(6301.5)$  during the flare. The non-monotonous evolution of this parameter implies non-monotonous changes of the magnetic field modulus  $B$  in the unresolved fluxtubes.

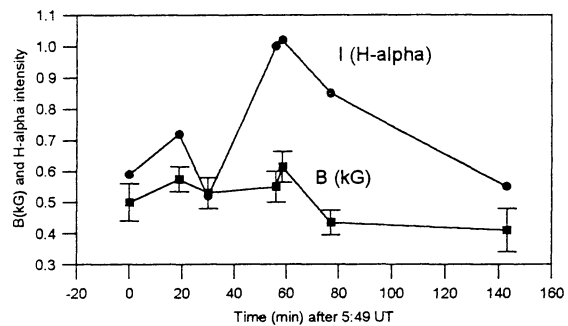


Figure 3. Variations of the mean magnetic field ( $B_{\parallel}$ ) and  $H\alpha$  intensity ( $I$ ) during the flare.

$$B_{\parallel} \approx \alpha B \cos \gamma \quad (7)$$

only in the case when the observed continuum intensity  $I_{co}$  equals to that in unresolved fluxtubes  $I_{cf}$ .

Values of  $B_{\parallel}$  from (6) and (7) may differ by about a factor of two. In particular, Koutchmy and Stellmacher (1978) have assumed  $I_{cf}/I_{co} = 1.8$  for a bright knot of photospheric network. During the flare this ratio could vary with time.

Measured values of  $\Delta\lambda_V$  for both FeI lines are given in Table 1 (typical errors of measurements are about  $\pm 2 m\text{\AA}$ ). One can see that the parameter  $\Delta\lambda_V$  varies more weakly for FeI 6301.5 than for FeI 6302.5 which is mainly caused by the lower Zeeman sensitivity of the first line. But in a general case similar changes may also arise due to the variation of the line center-to-continuum absorption coefficient  $\eta_0$  and the Doppler width  $\Delta\lambda_D$ . To eliminate these effects let us consider the line ratio  $\Delta\lambda_V(6302.5)/\Delta\lambda_V(6301.5)$ . For a weak magnetic field we can expect that

$$\frac{\Delta\lambda_V(6302.5)}{\Delta\lambda_V(6301.5)} \approx const \quad (8)$$

for all phases of a flare.

Table 1: *Observed Stokes V separations, average longitudinal field strengths, line ratios and H-alpha central intensities.*

Time (UT)	Phase of flare	$\Delta\lambda_V$ (mÅ)	$\Delta\lambda_V$ (mÅ)	$\frac{\Delta\lambda_V(6302.5)}{\Delta\lambda_V(6301.5)}$	$B_{  }$ (G)	I (H $\alpha$ )
h:min		for FeI 6301.5	for FeI 6302.5		from FeI 6302.5	observed
5:49.0	start	153	157	1.03	500	0.59
6:08.0	pre-peak	153	153	1.00	570	0.72
6:19.0	pre-peak	155	151	0.97	530	0.52
6:45.0	pre-peak	161	167	1.04	550	1.00
6:47.5	peak	165	185	1.12	615	1.02
7:06.0	post-peak	155	167	1.08	435	0.85
8:12.0	post-flare plage	145	129	0.89	410	0.55

The data given in the Table 1 imply that the case is different from the (8) assumption, i.e. there is a definite variation of the  $\Delta\lambda_V(6302.5)/\Delta\lambda_V(6301.5)$  line ratio during the flare (Figure 2). Such changes are signatures of the presence of small scale magnetic fluxtubes of kG strengths. The non-monotonous evolution of the above line ratio indicates non-monotonous changes of the magnetic field modulus  $B$  in the subtelescopic fluxtubes. One can see that the maximum of  $B$  happened exactly at the flare peak. Similar result was obtained earlier by Lozitska and Lozitskij (1994) for another 2B flare which had a flash phase. Perhaps these results are the manifestations of the phenomenon named 'magnetic transients in flares' by Zirin and Tanaka (1981). This problem was discussed by Lozitskaya and Lozitskij (1982). Extremely strong fields can arise at the upper photosphere or near to the temperature minimum zone (Lozitskij and Baranovskij, 1993; Lozitskij, 1993, 1998).

The other characteristics of the magnetic field, the longitudinal magnetic field  $B_{||}$  also exhibits non-monotonous variations. As follows from Figure 3, the changes of  $B_{||}$  were mainly synchronous with the temporal variations of the H $\alpha$  brightness obtained by the photometry of H $\alpha$  line from the Echelle spectra. Another interesting effect is also conspicuous in Figure 3: there is an obvious decrease of  $B_{||}$  after the peak with respect to its values before the peak. This provides a direct evidence for the transformation of magnetic energy into other types of energies released in the flare.

#### 4. SUNSPOTS AND H $\alpha$ STRUCTURES

The obtained data show that the sunspot proper motions in HR 17705 had some peculiarities. As the magnetic polarities were fairly mixed in the flaring region, mutual displacements of the spots of different polarities deserve special attention.

The most spectacular feature was the fast motion of the umbrae Nos. 42-44 of negative polarities in the direction of the positive 31-33-39-41 complex. The umbra 42 moved with high velocity and reached the penumbra 31 at about 10h UT. The other important factor in the flare generation is the umbra 40. This negative umbra emerged on the previous day extremely close to the common ancestor of the positive umbrae 33 and 31 and since then it had been receding from them to the East with a relatively large velocity. The largest flare knot

appeared on the eastern side of umbra 40 and another one appeared on the western side of it. The third flare knot between 33 and 31 and the fourth between 41 and 9 were also observed near the separation border of the opposite polarity regions.

These findings can be summarized in such a way that the flare knots were released at the interfaces of two squeezed regions or spots of opposite polarities, a similar example was also reported e.g. by Kovács (1977). Hints to the possible influence of shearing displacements are also perceivable as the positive 39-41-9-7-5-3-1 and the nearby negative 42-44-46-40 spots are moving along parallels into the opposite directions.

A hint to the re-distribution of field lines is provided by H $\alpha$  features: the negative 42,44 spots were connected to the positive 5-3-1 spots on the basis of the filament directions, whereas after the flare a loop appeared to be formed between 42-44 and 31. This might be interpreted as a consequence of the fact that the embedded negative area kept receding from the leading part and approaching the spot 31.

## 5. DISCUSSION

### 5.1. Field Strength

The field strength  $B$  is one of best determined parameter in the used model (see 3.1). However, this parameter can be measured directly from Stokes  $\Delta\lambda_V$  line ratio only in the case if  $\Delta\lambda_H/\Delta\lambda_D \geq 2.5$  and  $\eta_0 \ll 1$  (Lozitska & Lozitskij 1994). In a general case the above line ratio depends on both of the  $B$  and  $\gamma$  parameters. Since there are actually two unknown quantities ( $B$  and  $\gamma$ ), some additional data should be used. Such data can be the half-widths of the V-parameter peaks,  $\Delta\lambda_{1/2,V}$ , which depend on both  $\Delta\lambda_H/\Delta\lambda_D$  and  $\gamma$ .

An additional analysis showed that this problems may be solved if the used spectral lines have a sufficiently large ratio  $g\lambda^2/\Delta\lambda_{1/2}$ , where  $g\lambda^2$  is the factor of magnetic sensitivity and  $\Delta\lambda_{1/2}$  is the half-width of the line. As follows from the photometric atlas of Delbouille et al (1973), for undisturbed atmosphere this ratio equals (without a factor of  $10^9$ ) to 0.69, 1.04, 0.41 and 0.91 for the lines FeI 5247.1, FeI 5250.2, FeI 6301.5 and FeI 6302.5 respectively. In this connection, the pair FeI 5247/5250 is more suitable than FeI 6301/6302.

The obtained ratios  $\Delta\lambda_V(6302.5)/\Delta\lambda_V(6301.5)$  and  $\Delta\lambda_{1/2,V}(6302.5)/\Delta\lambda_{1/2,V}(6301.5)$  were insufficient to determine a reliable value of  $B$  without additional hypothesis. We can indicate only an upper field strength limit about 1.8 kG for the flare peak. Most likely, the middle value of  $B$  in other flare phases was about 1.5 kG.

On the other hand, the pair FeI 6301/6302 is attractive for magnetic field diagnostics in the extremely powerful flares because its temperature sensitivity is lower than for the pair FeI 5247/5250. In addition, for such flares the magnetic line ratios  $\Delta\lambda_V(6302.5)/\Delta\lambda_V(6301.5)$  and  $\Delta\lambda_{1/2,V}(6302.5)/\Delta\lambda_{1/2,V}(6301.5)$  are certainly more favourable.

## 5.2. Average Longitudinal Field $B_{\parallel}$

If the measured values of  $B_{\parallel}$  actually represented the average magnetic flux, then they could be used to estimate the magnetic energy changes during the flare. We take the field intermittence into account and use the values of  $B_{\parallel}$  in Table III as well as  $B \approx 1.5kG$  both before and after the flare. Thus the magnetic energy density is  $\alpha B^2/8\pi = BB_{\parallel}/8\pi$ . Before the peak  $B_{\parallel} \approx 550G$  whereas after the peak  $B_{\parallel} \approx 410G$ . Using the observed horizontal size of the flare knot of  $10arcsec = 7.26^8cm$  and assuming a vertical extension of  $10^8$  cm, the magnetic energy change is about  $4^{29}erg$ . This value is similar to the energies of optical solar flares (Kurochka et al. 1987).

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