PRE-FLARE CHANGES IN CURRENT HELICITY AND TURBULENT REGIME OF THE PHOTOSPHERIC MAGNETIC FIELD

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ABSTRACT

Measurements of the vector magnetic field in an active region NOAA 6757 were used to compare current helicity and turbulent regime of the magnetic field 2.5 - 0.5 hours prior and 2 minutes after the maximum of a strong 2B/X1.5 solar flare. First, we calculated the imbalance, ρ_h, of current helicity over the area of the flare. During a forty minute time interval, which includes the impulsive phase of the flare, total positive (negative) helicity decreased by 20% (27%), while the imbalance ρ_h changed from -5% to +1%. This implies that before the flare the necessary conditions for the α-effect in the solar photosphere were fulfilled, whereas after the flare maximum the generation of the electromotive force due to small-scale fluctuations of the magnetic field seems to be exhausted. Second, we calculated a cancellation exponent, k_h, of current helicity and an exponent, $\zeta(q)$, of structure functions of the longitudinal magnetic field. The curvature of $\zeta(q)$ indicates multifractality (intermittent turbulence) of the magnetic field, while k_h describes the intensity of oscillations of the sign of current helicity and, therefore, the strength of tangential discontinuities in the magnetic field. We found that the value of k_h was large until the last field measurement before the flare. After the flare maximum, the cancellation exponent was found to be significantly smaller. Meanwhile, observed behavior of $\zeta(q)$ implies that multifractality of the B_z component became more complicated before the flare, whereas, immideately after the flare maximum monofractality (non-intermittent turbulence) of the B_z component was set. Such changes in both k_h and $\zeta(q)$ complement each other as evidence that a flare can be treated as an avalanche of small-scale reconnections at tangential discontinuities of the magnetic field.

INTRODUCTION

Three sorts of helicity can be specified for magnetized plasma in the solar atmosphere, namely, kinetic, magnetic and current helicity: $H_k = \mathbf{v} \cdot (\nabla \times \mathbf{v})$, $H_m = \mathbf{A} \cdot (\nabla \times \mathbf{A})$ and $H_c = \mathbf{B} \cdot (\nabla \times \mathbf{B})$, respectively. Here, $\mathbf{v}$ denotes the fluid velocity and $\mathbf{A}$ is the magnetic vector potential. Current helicity is of particular importance for a problem of DC–magnetic energy build-up in the solar atmosphere (Seehafer, 1994): in order to the mean-field magnetic energy be prevented from decreasing, current helicities of mean and fluctuating magnetic fields should have opposite sign and the absolute value of the current helicity of fluctuations should exceed that of the mean-field. This implies that alpha-effect is operating in the solar atmosphere, which assumes the generation of non-zero electromotive force caused by magnetic field fluctuations.

Possessing a clear physical meaning (chirality of current-carrying flux tubes) current helicity is the only kind of helicity that can be now directly calculated from observational data. Having vector magnetic field measurements one can estimate a z-related part of the current helicity (Abramenko et al., 1996):

$$h_c = B_z \cdot (\nabla \times \mathbf{B})_z. \tag{1}$$

Analysis of current helicity in an active region was very fruitful for the study of total twist of magnetic structures in southern and northern hemispheres (Pevtsov et al., 1995; Abramenko et al., 1996; Bao and

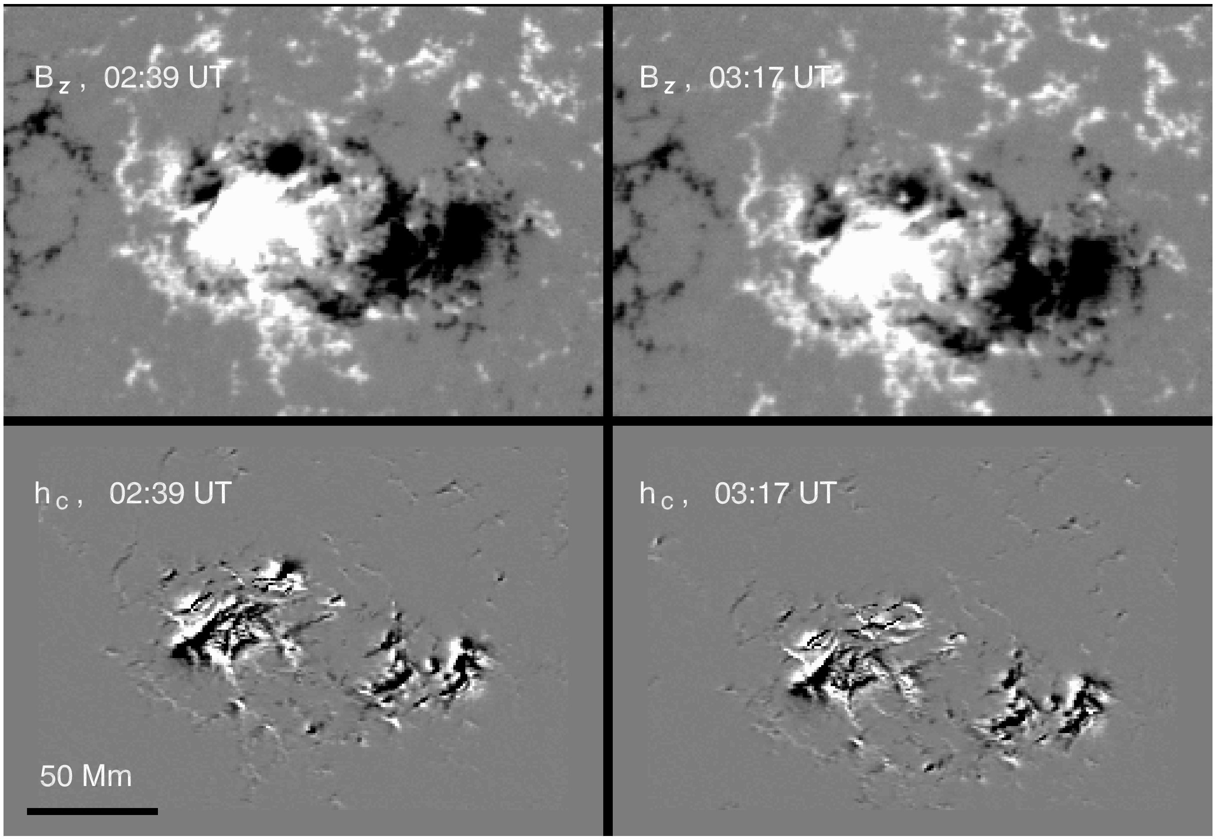

Fig. 1. B_z magnetograms (*top panel*) and current helicity maps (*bottom panel*) for NOAA AR 6757 obtained on August 2, 1991. North is to the top, west to the right.

Zhang, 1998). Scaling behavior of current helicity in active regions was previously analyzed by Abramenko et al. (1998). Yurchyshyn et al.(2000) have shown that periods of enhanced flaring are accompanied by reduced values of the cancellation exponent of current helicity - a parameter, which determines the strength of tangential discontinuities of the magnetic field. Therefore, properties of current helicity and their changes may help us to understand processes in an active region magnetic field during strong flares.

Here we compare structures of an active region magnetic field observed 2.5 - 0.5 hours before and 2 minutes after the maximum of a solar flare. For this purpose, we used routines to analyze current helicity (Abramenko et al., 1996) and structure functions (Abramenko, 2002).

CURRENT HELICITY BEFORE AND AFTER A STRONG FLARE

Our data set consists of four high-quality magnetograms of an NOAA active region 6757, which had been obtained on August 2, 1991 with the videomagnetograph at Huairou Solar Observing Station (Wang et al., 1996). The magnetograms are measurements of the vector magnetic field using the Fe I 532.4 *nm* spectral line with the pixel size of $0.62'' \times 0.43''$ (see Yurchyshyn et al., 2000).

A 2B/X1.5 flare started at 03:07 UT, peaked at 03:15 UT, and ended at about 04:07 UT. Three magnetogmams were taken before the flare at 00:36 UT, 02:00 UT and 02:39 UT. The last magnetogram was taken at 03:17 UT - two minutes after the flare maximum.

$2D$-structures of current helicity were calculated for each vector magnetogram according to Eq. (1). The vertical component, B_z, of the magnetic field and current helicity, h_c, for magnetograms at 02:39 UT and 03:17 UT are shown in Figure 1.

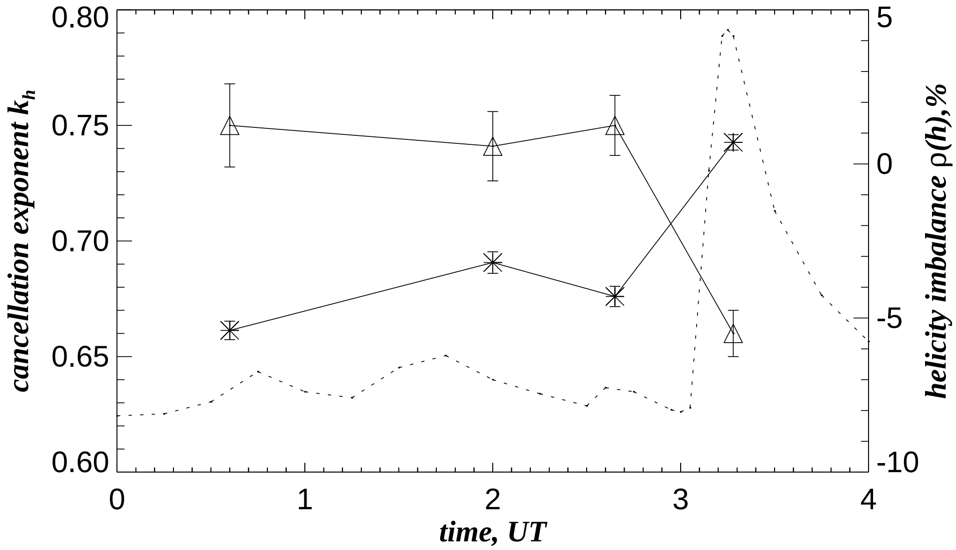

Fig. 2. Time variations of the helicity imbalance, ρ_h (right axis, *stars*), and of the cancellation exponent, k_h, of current helicity (left axis, *triangles*). The dotted line shows GOES X-ray flux, in arbitrary units, with the background level at C2 and the peak at X1.5.

We calculated the imbalance of current helicity, ρ_h, by using a relation given by Abramenko et al (1996):

$$\rho_h = \left(\sum_{S_+} |h_c(x,y)| - \sum_{S_-} |h_c(x,y)| \right) / \left(\sum_{S_+} |h_c(x,y)| + \sum_{S_-} |h_c(x,y)| \right) \times 100, \% \tag{2}$$

where S_+ is a set of pixels with $h_c(x,y) > 0$ and S_- is a set of pixels with $h_c(x,y) < 0$. Values of ρ_h for four consecutive magnetograms are shown with stars in Figure 2, right axis. Before the flare the imbalance was slowly decreasing and negative, implying the counter clockwise (CCW) total twist of the magnetic structure, which is typical for active regions in the northern hemisphere. After the flare maximum the imbalance already became a small positive value of about 1%. Thus, from 2:39 UT untill 3:17 UT both the absolute value and the sign of ρ_h had changed. These changes of the imbalance during the flare are more rapid than those seen in the pre-flare period. We would like to note, that similar abrupt flare related changes of current helicity were reported before (Pevtsov et al., 1995; Bao et al., 1999).

In our case the observed changes in ρ_h were accompanied by the 20% (27%) decrease in total positive (negative) helicity, while the total fluxes of the longitudinal magnetic field and electric current were reduced by only 3% and 6%, respectively. Therefore, taking into account Eq(1), one cames to a conclusion that the observed reduction of total negative and positive helicities can only in part be accounted by the decrease of total fluxes of the magnetic field and electric current. The changes of the sign of the imbalance are mostly due to reorganization of the twist of current carrying structures. The low value of ρ_h at 3:17 UT implies that there was no predominant helicity after the flare maximum. Thus, before the flare the necessary conditions for the α-effect were met (Seehafer, 1994), whereas after the flare maximum the generation of the electromotive force due to small-scale fluctuations of magnetic field seems to be exhausted.

In order to reveal changes of the magnetic field at small scales we analyzed scaling behavior of current helicity (Abramenko et al., 1998). For this purpose we calculated a signed measure :

$$\mu_i(r) = \frac{\int_{L_i(r)} h_c(x,y)dxdy}{|\int_{L(R)} h_c(x,y)dxdy|}, \tag{3}$$

where $L_i(r) \subset L(R)$ is a hierarchy of disjoint squares of size r, covering the whole square $L(R)$, which enclose

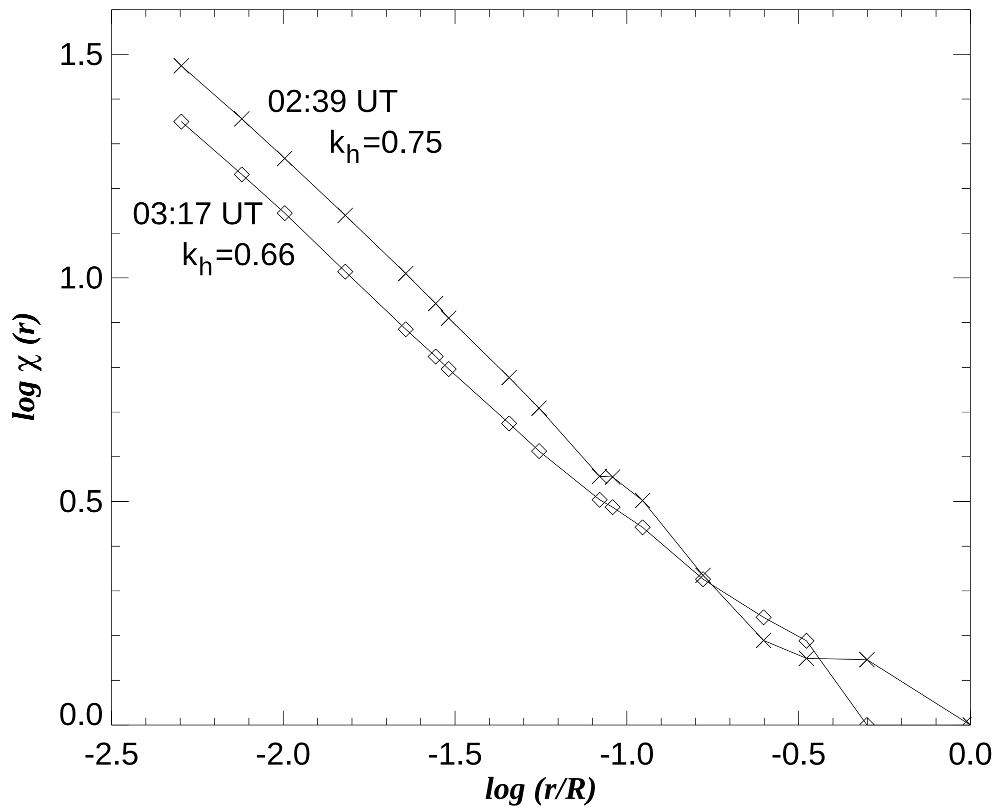

Fig. 3. Partition functions, $\log\chi(r)$ vs $\log(r/R)$, for two magnetograms recorded before the flare at 02:39 UT (*crosses*) and two minutes after the flare peak at 03:17 (*diamonds*). The slope of partition functions – *cancellation exponent* k_h – was estimated over the scale interval of 1 - 48 Mm. Errors of calculations are smaller then the size of the symbols.

the active region. Then, we investigated behavior of the alternate in sign, scale by scale, of the measure by defining a cancellation exponent k_h (Ott et al, 1992)

$$\chi(r) = \sum_{L_i(r)} |\mu_i(r)| \sim r^{-k_h}. \tag{4}$$

Parameter k_h is an indication of how rapidly cancellations between negative and positive contributions happen as the spatial scale becomes smaller. In general, the stronger the oscillation of the helicity sign (and therefore, the strength of tangential discontinuities in the magnetic field), the higher the value of k_h. The partition functions $log\chi(r)$ vs $log(r/R)$ are shown in Figure 3. One can see that after the flare peak (at 3:17 UT) the slope of partition function became smaller then it was before the flare.

The time variations of the cancellation exponent are shown in Figure 2 (*triangles*). One can see that until 28 minutes before the flare onset the value of k_h remains high at the level about 0.75, whereas at about 2 min after the flare maximum it is rapidly decreased down to 0.66. This means that the strength of tangential discontinuities of the magnetic field is significantly reduced by a flare, which supports Parker's idea about the principal cause of a solar flare as an avalanche of many very small reconnection events (Parker, 1987).

Signatures of an avalanche can also be recognized in other way, namely, by analyzing the turbulent state of the magnetic field. For turbulence within the inertial range at large magnetic Reynolds numbers, the B_z component of the magnetic field diffuses in exactly the same way as a scalar field (see, for example, Parker, 1979; Petrovay and Szakaly, 1993). So, some elements of the analysis of turbulent systems can be applied

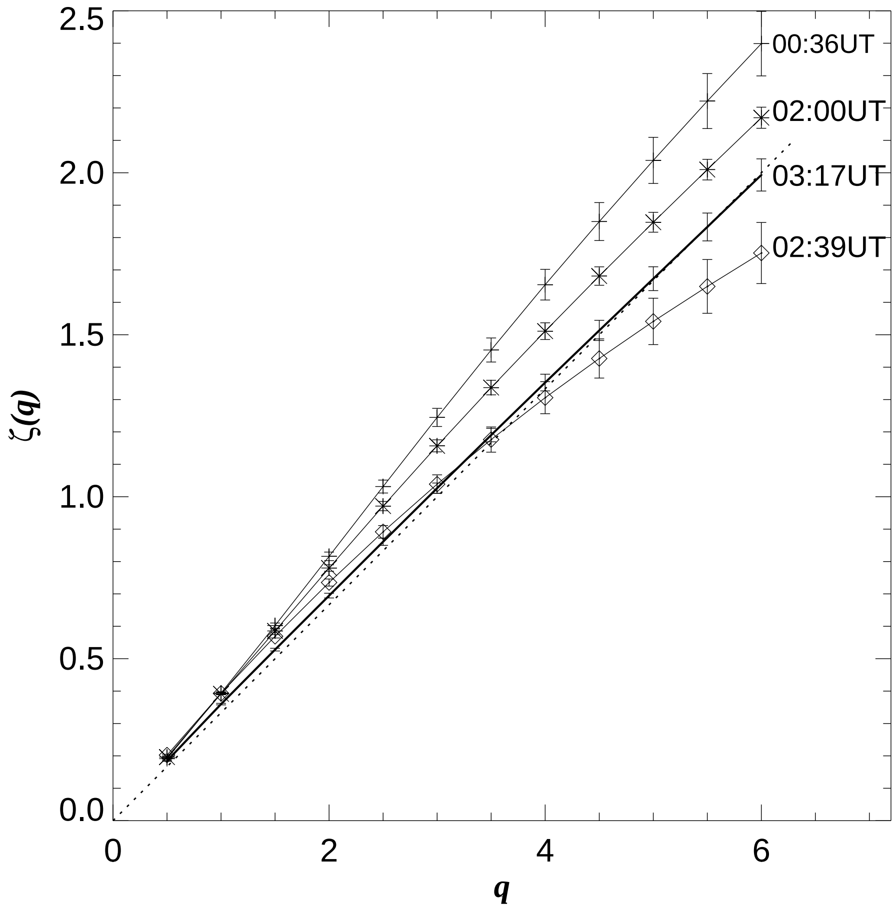

Fig. 4. Exponents $\zeta(q)$ of structure functions of the order of q versus q calculated for four magnetograms. The Kolmogorov's straight line of the slope of $1/3$, corresponding to non-intermittent turbulence, is shown by the dotted line. The thick line shows $\zeta(q)$ after the flare maximum.

for B_z. In particular, according to a routine proposed recently (Abramenko 2002), we calculated structure functions

$$S_q(r) = \langle |B_z(\mathbf{x}+\mathbf{r}) - B_z(\mathbf{x})|^q \rangle \sim (r)^{\zeta(q)} \tag{5}$$

and we plot their exponents $\zeta(q)$ in Figure 4.

One can see that $\zeta(q)$ is a concave outward function, whose curvature gradually increases as the active region evolves toward the flare. Such behavior of $\zeta(q)$ implies that the multifractality of B_z component of the magnetic field becomes more complicated. Immediately after the flare maximum the function $\zeta(q)$ nearly coincides with the classical Kolmogorov's straight line (dotted line in Figure 4), which indicates a monofractal structure of the B_z-component in the active region.

The transition from multifractality to monofractality is a manifestation of an avalanche in a complex magnetic structure accompanied by reduction of small-scale tangential discontinuities in the magnetic field (Parker, 2002).

CONCLUSIONS

In summary, comparison of current helicity and turbulent state of the magnetic field in an active region before and after the flare maximum allowed us to conclude the following.

1. Negative imbalance of current helicity of about -5% observed before the flare was turned into low

positive imbalance of about 1% immideately after the flare maximum. In the meantime, total positive (negative) helicity decreased by 20% (27%).

2. Values of the cancellation exponent, k_h, of current helicity decreased from 0.75 to 0.66 within a 38 minute time interval during which a flare started and reached its maximum.

3. The structure functions of the B_z component of the magnetic field indicated the transition from intermittent turbulence (multifractality) before the flare to non-intermittent turbulence (monofractality) after the flare peak.

Observed changes in current helicity are a manifestation of intrinsic processes in the magnetic field, which drive an active region to the flare. The character of the changes supports the following ideas. First, flares are a result of an avalanche of small-scale magnetic reconnection events cascading through a highly stressed magnetic configuration, driven to a critical state by random photospheric motions (Parker, 1987, Charbonneau et al., 2002). Second, the build up of DC magnetic energy in the solar atmosphere due to small-scale fluctuations of the magnetic field can take place at least for several hours before a flare (Seehafer, 1994).

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