

Topological changes of the photospheric magnetic field inside active regions: A prelude to flares?

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Received 18 July 2002; accepted 3 February 2004

Abstract

The detection of magnetic field variations as a signature of flaring activity is one of the main goals in solar physics. Past efforts gave apparently no unambiguous observations of systematic changes. In the present study, we discuss recent results from observations that scaling laws of turbulent current helicity inside a given flaring active region change in response to large flares in that active region. Such changes can be related to the evolution of current structures by a simple geometrical argument, which has been tested using high Reynolds number direct numerical simulations of the MHD equations. Interpretation of the observed data within this picture indicates that the change in scaling behavior of the current helicity seems to be associated with a topological reorganization of the footprint of the magnetic field loops, namely with the dissipation of small scales structures in turbulent media.

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Keywords: Active regions; Flares

1. Introduction

Solar flares are sudden, transient energy release processes in active regions on the Sun (Priest, 1982). As a consequence of random motions of footpoints of the magnetic field loops in the photospheric convective media (Parker, 1987), magnetic energy is dissipated at numerous tangential discontinuities which arise spontaneously in magnetic fields of active regions. The magnetic energy is released in various forms as thermal energy, kinetic energy and accelerated particles. The observations of magnetic field variations, as a signature of flares in active regions, is one of the main goals in solar physics, and some attempts to determine these have been made in the past (e.g. Hagyard et al., 1999 and references therein). All efforts give apparently no unambiguous observations of changes. Recently, observations of changes have been reported by Yurchyshyn et al. (2000). The authors observed systematic changes of the scaling

behavior of the current helicity from analysis of images of the photospheric magnetic field inside an active region, connected to the eruption of large flares above that active region. In the present paper we conjecture that the changes in the scaling behavior of such observed quantities are related to the occurrence of changes in the topology of the magnetic field at the footprint of the loop.

2. Cancellation analysis and topology of turbulent structures

The occurrence of scaling of signed measures, calculated from scalar fields $f(x)$ which oscillate in sign, can be studied by using ‘cancellation’ analysis. For a given scalar field $f(x)$, with $x \in Q(L)$ where L is the size of the domain, we introduce a coarse-graining of non-overlapping boxes $Q_i(r)$ of size r , covering the whole domain $Q(L)$. For each box $Q_i(r)$ a signed measure $\mu_i(r)$ is defined as

$$\mu_i(r) = \int_{Q_i(r)} f(x) dx, \quad (1)$$

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where i changes from 1 to the number of boxes $Q_i(r)$ needed to cover $Q(L)$ at the scale r . The box size r is thus a parameter representing a typical scale length. A partition function $\chi(r)$ can also be introduced by summing the signed measures $\mu_i(r)$ over all boxes covering the region $Q(L)$ at a given scale r

$$\chi(r) = \sum_{Q_i(r)} |\mu_i(r)|. \quad (2)$$

It had been observed that for fields presenting self-similarity, this quantity displays well-defined scaling laws (Ott et al., 1992). That is, in a range of scales r , the partition function follows a power-law behavior

$$\chi(r) \sim r^{-\kappa}. \quad (3)$$

The scaling exponent κ is called a ‘cancellation exponent’ (Ott et al., 1992) because it represents a quantitative measure of the scaling behavior of the imbalance between negative and positive contributions in the measure. For a positive definite measure, or for a smooth field, $\kappa = 0$, while $\kappa = d/2$ for a completely stochastic field in a d -dimensional space (for example, a field of uncorrelated points with $f = \pm 1$, the sign being chosen randomly and independently for each point, with probability $\frac{1}{2}$). As the cancellations between negative and positive parts of the measure decreases toward smaller scales, κ becomes positive. It is clear that the presence of various structures in a scalar field have an important effect on the cancellation exponent. For example, values of $\kappa < d/2$, (in the present paper $d = 2$), indicate the presence of sign-persistent (i.e. smooth) structures.

In turbulent flows, the value of the cancellation exponent can be related to the characteristic fractal dimension D of turbulent structures on all scales using a simple geometrical argument (Sorriso-Valvo et al., 2002). Let λ be the typical correlation length of these structures, of the order of the Taylor micro-scale (see for example Frisch, 1995). In this case a scalar field is smooth (correlated) in D dimensions with a cutoff scale λ , and uncorrelated in the remaining $d - D$ dimensions. In this sense, the dimension D represents the correlation dimension of the field. If the field is homogeneous, the partition function (2) can be computed as the number of boxes of size r , namely $(L/r)^d$, times the integral over a single generic box $Q(r)$

$$\chi(r) = \sum_{Q_i(r)} \left| \frac{\int_{Q_i(r)} \mathbf{d}\mathbf{x} f(\mathbf{x})}{\int_{Q(L)} \mathbf{d}\mathbf{r} |f(\mathbf{x})|} \right| \sim \frac{1}{L^d f_{\text{rms}}} \left(\frac{L}{r} \right)^d \left| \int_{Q(r)} \mathbf{d}\mathbf{x} f(\mathbf{x}) \right|. \quad (4)$$

The scaling of $\chi(r)$ can then be estimated by integrating the signed measure $\mu(r)$ over smaller regular sub-boxes of size λ^d recovering the box $Q(r)$. The integration of the field over each sub-box of size λ in which the field is smooth returns the r.m.s. value of the field, namely $f_{\text{rms}} = \langle f^2 \rangle^{1/2}$, where brackets indicate the average over the whole domain

$Q(L)$. The number of contributing sub-boxes can be estimated by considering separately the correlated dimensions of the field and the uncorrelated ones. Integration over correlated dimensions bring a contribution proportional to their area $(r/\lambda)^D$, while the uncorrelated dimensions contribute as integral of the uncorrelated field, that is proportional to the square root of their area $(r/\lambda)^{(d-D)/2}$. Thus, when homogeneity is assumed, collecting all the contributions in (2) leads to the following partition function:

$$\chi(r) \sim \frac{\lambda^d f_{\text{rms}}}{L^d f_{\text{rms}}} \left(\frac{L}{r} \right)^d \left(\frac{r}{\lambda} \right)^D \left(\frac{r}{\lambda} \right)^{(d-D)/2} \sim \left(\frac{r}{\lambda} \right)^{-(d-D)/2} \sim \left(\frac{r}{\lambda} \right)^{-\kappa} \quad (5)$$

so that one can recover the simple relation

$$\kappa = (d - D)/2. \quad (6)$$

3. Cancellation analysis of active region magnetograms

To get a quantitative measure of a change in the scaling of current helicity inside an active region, we used observations of the vector magnetic field obtained with the Solar Magnetic Field Telescope of the Beijing Astronomical Observatory (China). Measurements were recorded in the Fe I 5324.19 Å spectral line. The field of view is about $218'' \times 314''$, corresponding to 512×512 pixels on a CCD. The magnetic field vector at the photosphere was obtained by measuring four Stokes parameters. The current density $J_z(x, y)$ was calculated as a contour integral of the transverse field over a closed contour of size $1.72'' \times 1.86''$ (cf. Yurchyshyn et al., 2000, for details). The current helicity, $H_c = \mathbf{B} \cdot \mathbf{J}$, where \mathbf{B} represents the magnetic field and $\mathbf{J} = \nabla \times \mathbf{B}$ is the current density, is a measure of small-scale activity in magnetic turbulence. It indicates the degree of clockwise or counter-clockwise twisting of current structures. Let us consider a photospheric magnetogram of size L taken in an active region and let $\mathbf{B}_\perp(x, y)$ be the observed transverse magnetic field perpendicular to the line of sight, where (x, y) are coordinates on the surface of the sun. By using this transverse field, we can calculate the restriction of the current helicity to the z -components of the fields, or in short the z -related part of current helicity, namely $h_c(x, y) = B_z(x, y)J_z(x, y)$, where $J_z(x, y) = [\nabla \times \mathbf{B}_\perp] \cdot \hat{\mathbf{e}}_z$. For simplicity, in this paper we will in fact refer to the z -related part of current helicity as current helicity. Fig. 1 shows the current helicity calculated for an active region NOAA 7590 for a given time, which is close to the time of a flare. The presence of signed structures is clearly visible.

A signed measure can be defined from the current helicity as follows:

$$\mu_i(r) = \int_{Q_i(r)} h_c(x, y) \mathbf{d}x \mathbf{d}y. \quad (7)$$

In Fig. 2 we show, as an example, the scaling behavior of $\chi(r)$ vs. r for flaring active region NOAA 7315, which

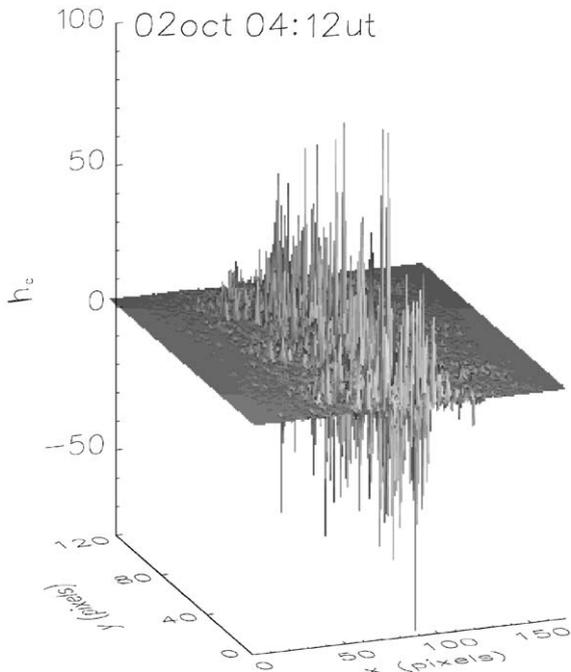


Fig. 1. The current helicity h_c determined for the active region NOAA 7590 on October 3, 1992. The presence of positive and negative structures on all scales is clearly visible. The flat portion of field near the corners arise due to the removal of projection effects.

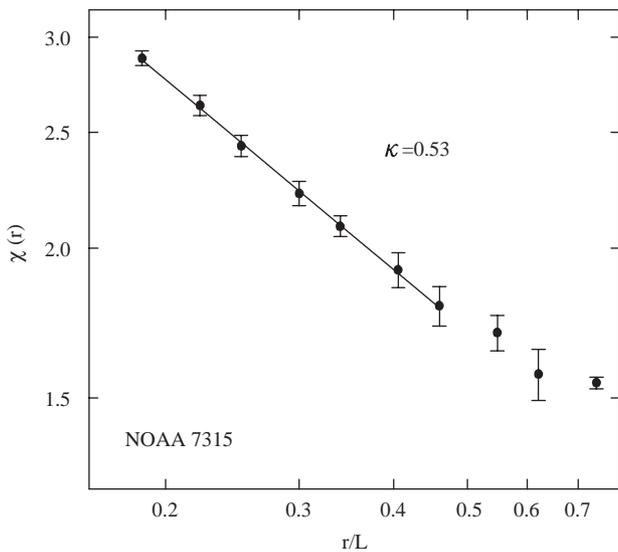


Fig. 2. An example of the scaling of the partition function for a flaring active region (NOAA 7315), which started to flare on October 22, 1992. The power-law fit is indicated as a solid line.

started to flare on October 22, 1992. At large scales we find $\chi(r) \sim const$, which is due to the complete balance between positive and negative contributions. If the resolution of the magnetograms was high enough to resolve the small structures of current helicity, the partition function shown in

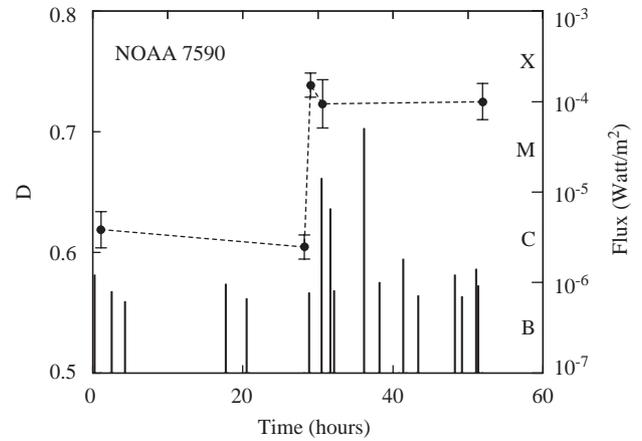


Fig. 3. Flare intensity in W/m^2 recorded in active region NOAA7590, including one large M-class flaring event, observed October 1–3, 1993 (line bars, right vertical axis). The corresponding time variation of the fractal dimension D is reported with symbols linked by a dashed line (left vertical axis).

Fig. 2 would also saturate at small scales. This is not seen in the data, indicating the presence of structures smaller than the resolution scale of the magnetograms used. In the intermediate range of scales, the cancellation exponent is found to be 0.53 ± 0.09 (Yurchyshyn et al., 2000).

Let us now consider how the fractal dimension of current structures D changes as a function of time. To this aim, we take a set of consecutive magnetograms of the same active region and for each magnetogram we compute the values of κ and D by using relation (6). Note that, since cancellations in the vertical photospheric magnetic field $B_z(x, y)$ have been found to be very small (Lawrence et al., 1993; Abramenko et al., 1998a), with a cancellation exponent of the order of 10^{-2} , cancellations in the current helicity are entirely due to current structures.

As an example, in Fig. 3, we show the time evolution of D compared to the X-ray flux measured in an active region NOAAs 7590.

We observe that the fractal dimension D , abruptly increases in correspondence with a sequence of large (C and M class) flares, with flux above $10^{-6} W/m^2$, occurring in the corona. The same behavior has been found for all calculations in all active regions with major flares we examined (more examples are reported in Abramenko et al., 1998a; Yurchyshyn et al., 2000; Abramenko, 2002). The detailed analysis of the cancellation exponent variations is reported in Yurchyshyn et al. (2000). The values of the fractal dimension D for five active regions are given in Table 1, together with the occurrence of C-class or larger flares. From this analysis, it seems that the fractal dimension D presents jumps only if major flares are observed. In fact, in a very quiet active region (see AR7216 values in Table 1), variations of D are of the order of 10%, against the 30–40% observed in all other active regions with large flares. Apart from this, no correlation has been found between the value of the jump

Table 1

For five active regions, we report the values of the fractal dimension D of the photospheric magnetic structures, as computed from the cancellation exponents, following our model (see text). The start times and the classes of large flaring events occurring in the corresponding active regions, are also indicated. All times are measured in hours, starting from the first magnetogram for each AR (taken at $t = 0.00$). Note that the first active region does not present large flares

AR	time (h)	time (class) of flare	D
7216	0.00	—	0.894 ± 0.020
	1.10	—	0.986 ± 0.006
	2.55	—	0.902 ± 0.020
	3.68	—	0.952 ± 0.010
	4.85	—	1.000 ± 0.016
7315	0.00	—	0.952 ± 0.008
	—	20.75 (C)	—
	—	21.62 (C)	—
	22.78	—	0.920 ± 0.012
	—	22.82 (M)	—
	23.02	—	1.170 ± 0.014
	25.05	—	1.300 ± 0.008
	47.45	—	1.286 ± 0.008
	48.67	—	1.256 ± 0.012
51.02	—	1.090 ± 0.010	
7590	0.00	—	0.476 ± 0.014
	26.50	—	0.418 ± 0.020
	—	27.18 (M)	—
	27.35	—	0.954 ± 0.004
	—	28.77 (M)	—
	28.92	—	0.892 ± 0.008
51.98	—	0.900 ± 0.006	
7585	0.00	—	0.776 ± 0.012
	—	2.53 (C)	—
	3.37	—	1.178 ± 0.010
	3.52	—	1.218 ± 0.008
	—	4.10 (B)	—
	4.37	—	1.108 ± 0.012
	5.75	—	0.978 ± 0.012
23.53	—	0.892 ± 0.012	
6891	2.38	—	1.008 ± 0.006
	0.47	—	0.932 ± 0.006
	1.28	—	0.672 ± 0.010
	2.63	—	0.886 ± 0.006
	—	2.95 (C)	—
	—	3.25 (X)	—
	3.47	—	0.930 ± 0.008
4.45	—	0.746 ± 0.008	

of D and the intensity of the associated sequence of large flares.

As we have already mentioned, as the density of the measure becomes smooth (no changes in sign are present) we may see a saturation of $\chi(r)$. As shown in Fig. 2, saturation of $\chi(r)$ is observed at large scales. The fact that we do not find this saturation at the small scales is indirect evidence that current helicity structures are smaller than the spatial resolution of the data. The change toward large D , indicating

smoothing of small-scale current structures, is then, probably, due to small-scale dissipation of magnetic energy. That is, magnetic energy is suddenly transferred toward small scales, as a manifestation of a turbulent energy cascade.

4. Cancellation analysis of numerical data

The model linking the fractal dimension of structures with the cancellation exponent can be tested using numerical data. We point out that the numerical data used in this section is not supposed to simulate the complexity of actual photospheric plasma. However, we use such data in order to check the validity of model (6) in a simpler context.

Using high-resolution turbulent fields, obtained from two-dimensional ($d = 2$), periodic, incompressible, forced magnetohydrodynamic simulations (Politano et al., 1998; Sorriso-Valvo et al., 2000), we can build-up different signed measures. For example, since the geometry of the magnetic field $\mathbf{B}(x, y) = (B_x, B_y, 0)$ is two-dimensional, the current $\mathbf{J}(x, y) = \nabla \times \mathbf{B} = (0, 0, J_z)$ has only a z component. In Fig. 4 we display the electric current field $J_z(x, y)$, obtained from our numerical data. The gray-scale map shows one snapshot of the field in a statistically steady state, during a time interval starting at $t = 168$ until $t = 336$. Note that time is measured in non-linear time units, τ_{NL} , based on the rms velocity and the integral scale. As in the case of the observed solar data, the presence of positive and negative current structures is evident in the simulated image (Fig. 4). The

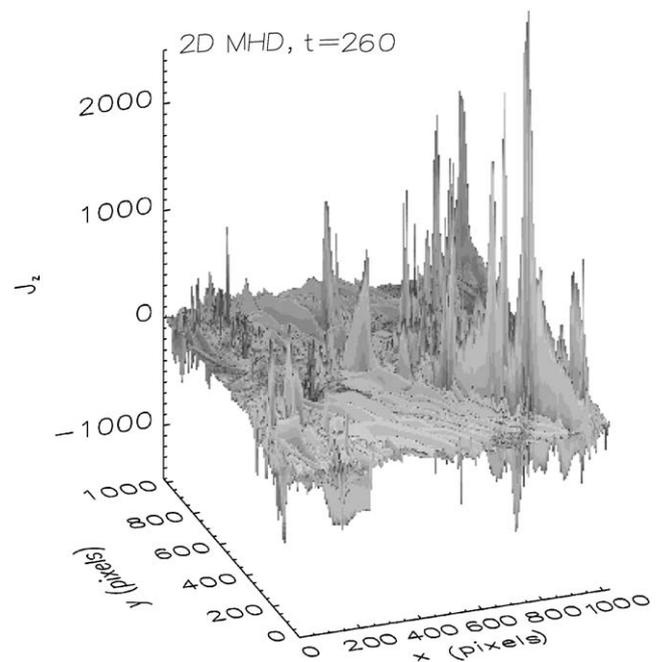


Fig. 4. Current field J_z obtained from a high-resolution two-dimensional numerical simulation of the MHD equations. The plot refers to one snapshot in the statistically steady state, at $t = 260$ in non-linear time units, τ_{NL} . As in the case of the solar data, the presence of positive and negative structures on all scales is clear.

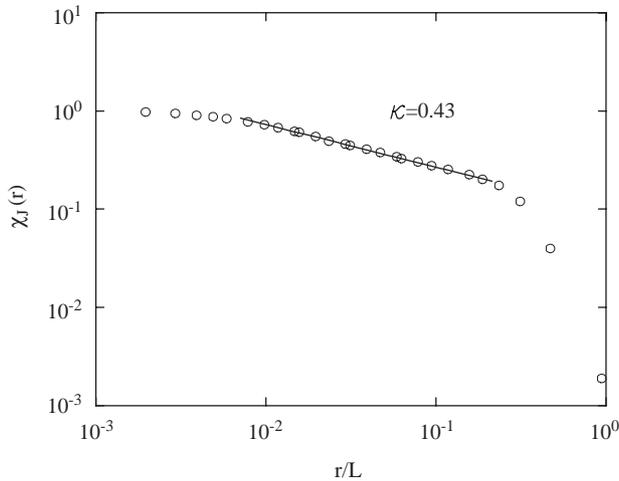


Fig. 5. Scaling of the current partition function stemming from numerical data. This result is obtained by averaging the time evolution, in order to increase the quality of the statistics. A power-law fit is indicated as a straight line. The scales are normalized to the simulation box size $L = 2\pi$.

signed measure of electric current can be then computed as

$$\mu_i(r) = \int_{Q_i(r)} J_z(x, y) dx dy$$

and the scaling properties of the current partition function $\chi_J(r)$ are reported in Fig. 5. Note that the current partition function presented in Fig. 5 is computed as the time average in the statistically steady time interval mentioned above. The power-law scaling (3) is clearly visible in a spatial range extending from the large scales (near the integral scale of the flow $\ell_0 \sim 0.2L$, $L = 2\pi$ being the size of the simulation box) down to less than the correlation length r^* of the order of the Taylor micro-scale of the flow $\lambda \sim 0.02L$ (see for example Frisch, 1995). In this region, the fit to the partition function yields the cancellation exponent $\kappa = 0.43 \pm 0.06$. A saturation of the partition function is observed at a scale r_S which is found to be of the order of the dissipative scale of the flow. In fact, for scales smaller than r_S the dissipation stops the cascade of formation of small-scale structures, therefore cancellations end too. The fractal dimension of current structures is computed using Eq. (6), which gives $D \simeq 1$, indicating that current structures are similar to filaments. The presence of current filaments can be clearly observed by a direct inspection of the current field contour plot, confirming the reliability of the model (see Sorriso-Valvo et al., 2002).

In order to directly compare the numerical results with the observed solar data cancellation analysis, we calculate the current helicity for the model field. As mentioned before, in two-dimensional geometry, the electric current is perpendicular to the magnetic field, hence the current helicity is zero; we thus simply consider $H_c^{(2d)}(x, y) = J(x, y)|B(x, y)|$, which is shown in Fig. 6 for the same time as in Fig. 4. The modeled current helicity, as in the case of the solar data, appears smoother than the electric current map, and has the same topology of structures. The signed measure of such a

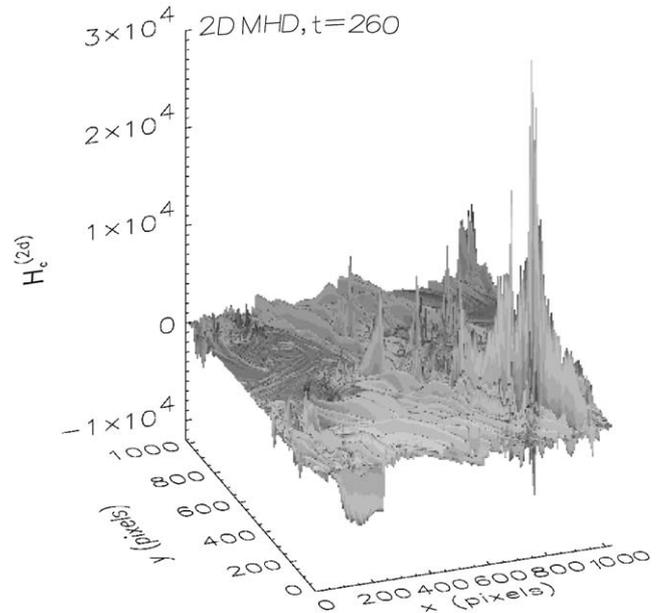


Fig. 6. Current helicity $H_c^{(2d)}$ obtained from a high-resolution two-dimensional numerical simulation of the MHD equations (same snapshot as that presented for the current in Fig. 4). Signed structures are present and reproduce the current structures, but the current helicity field looks smoother than the current field itself.

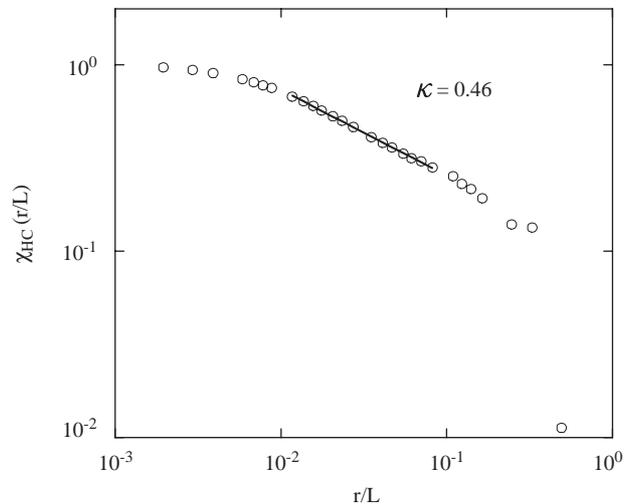


Fig. 7. Scaling of the partition function for the current helicity stemming from numerical data. As for the current, this result is obtained by averaging the time evolution, in order to increase the statistics. The power-law fit is indicated as a straight line. The scales are normalized to the simulation box size $L = 2\pi$.

field is then computed as in previous cases

$$\mu_i(r) = \int_{Q_i(r)} H_c^{(2d)}(x, y) dx dy.$$

The scaling properties of the partition function $\chi_{H_c}(r)$ can now be represented by a cancellation exponent, obtained by the usual fitting procedure after time averaging. In Fig. 7 we present the scaling of $\chi_{H_c}(r)$ along with the power-law fit-

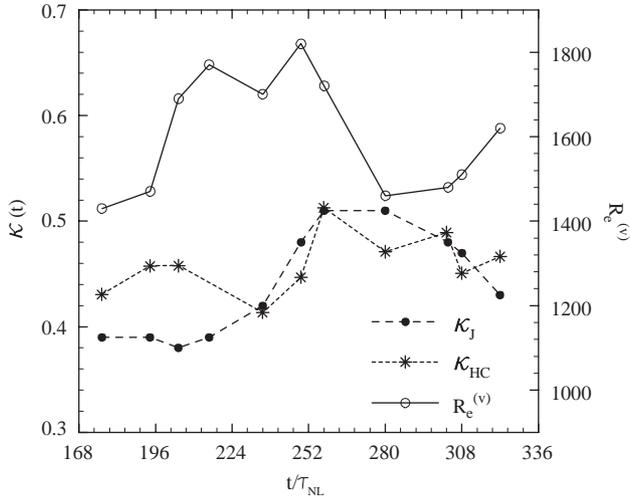


Fig. 8. Cancellation exponents for both the current κ_j (black circles) and the current helicity κ_{H_c} (stars) for different times (left vertical axis). The plot with open circles represents the kinetic Reynolds number $R_e^{(v)}$ of the flow (right vertical axis).

ting with the power index $\kappa = 0.46 \pm 0.03$. This index is close to that obtained for the electric current; this shows that in the case of the two-dimensional numerical simulations presented here, the current field is the one responsible for sign singularities, and the current structures control the cancellations. However, it remains to be confirmed, e.g. with the help of three-dimensional numerical simulations, whether indeed all such correlation functions built on the magnetic field and its derivatives have identical scaling laws.

We now consider in more detail the time evolution of cancellation effects in the two-dimensional numerical simulations. To do this, we plot in Fig. 8 the time evolution of the (kinetic) Reynolds number, together with the two cancellation exponents κ_j and $\kappa_{H_c^{(2d)}}$, for the snapshots already presented in Figs. 4 and 6.

The time evolution of the Reynolds number is shifted (time-lag) with respect to the evolution of the cancellation exponents. Unfortunately, due to the limited time interval of our simulations, it is impossible to say whether that shift is backward or forward. Since the Reynolds number is related to the importance of dissipative effects against non-linear effects in the turbulent cascade, it would be interesting to clarify this question as a further confirmation of our interpretation. This point is left for future work.

Moreover, in Fig. 9 we plot 10 snapshots of the current helicity field $H_c^{(2d)}$, taken within the time interval between $t = 168$ and 336.

5. Conclusions

In this paper we build a model which allows us to recognize changes in the behavior of the photospheric magnetic field of active regions. These changes, detected by variations of a scaling index for turbulent cancellations of the current helicity, are mainly observed before the start of a sequence of large (C-class or larger) flares occurring in the corona.

The variations of the scaling index are due to topology changes of the structures present in the magnetic field, and, thus, are related to the non-linear, intermittent turbulent cascade, underlying the formation of such structures. This

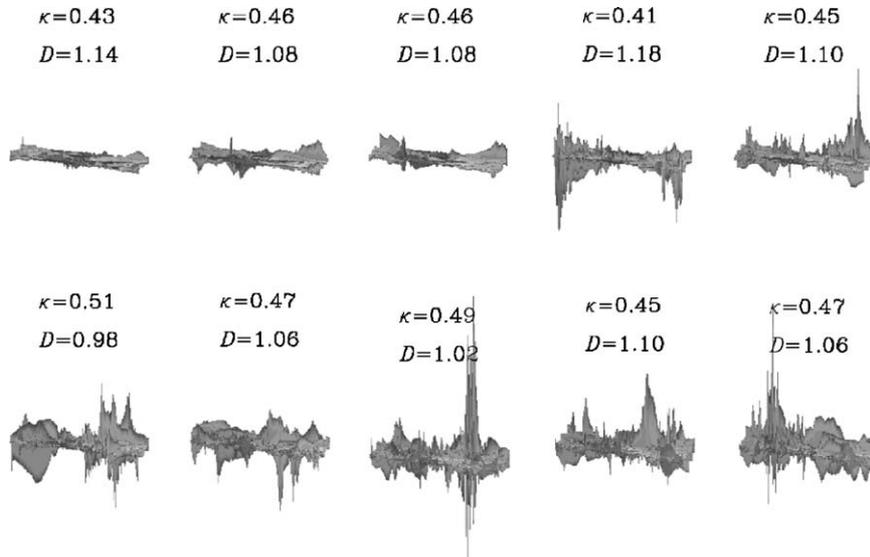


Fig. 9. Time evolution of the current helicity field $H_c^{(2d)}$, obtained from a high-resolution two-dimensional numerical simulation of the MHD equations with ten snapshots in the statistically steady state. For each snapshot, the values of the cancellation exponent κ and the fractal dimension D are reported. The frames are dropped for clarity.

suggestion has been tested using high-resolution numerical data. The topological changes of the magnetic structures are linked to small-scale dissipation. Thus, our picture supports the idea of E. Parker concerning an avalanche of small reconnection events as the main cause of solar flares (see Parker, 1987; see also Abramenko et al., 1998a). Recently, an analysis of the intermittency variations during flares by Abramenko et al., 1998a) also supported this picture.

However, we have to point out that the temporal resolution of the solar data is poor. Unfortunately, this kind of observations needs several restrictive conditions, namely a strong flare, an active region near the solar disk center, telescope day-time at an observatory, good seeing, several magnetograms before the flare and, at least, one at the flare maximum, conditions which are seldom met. Nevertheless, the behavior observed for the five cases reported in Table 1, as well as in the other cases found in the literature (Abramenko et al., 1998b) suggests that the preliminary results presented here are significant enough to encourage a search for similar correlations, and to explore more thoroughly the fine structure of flares, in order to be able to obtain all the necessary information leading to the computation of the fractal dimension D , and, thus, to improve the temporal resolution of the observations.

To conclude, the analysis presented here indicates what should be a candidate signature of the occurrence of large flares, the cancellation analysis giving information about the physical statistical processes underlying flares. It could then be considered as a useful tool in the attempt to forecast the occurrence of strong flaring activity in active regions.

Acknowledgements

Part of this work was completed during a visit of LSV at the Observatoire de la Côte d'Azur, supported by the French

Ministry of Research and Education. Comments of an anonymous referee were also helpful in improving this article.

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