Cancellations and structures in the solar photosphere: signature of flares

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Abstract. The topological properties of the typical current structures in a turbulent magnetohydrodynamic flow can be measured using the cancellations analysis. In two-dimensional numerical simulations, this reveals current filaments being the most typical current structures. The observations of the topology of photospheric current structures within active regions shows that modifications occur correspondingly with strong flares.

INTRODUCTION

Solar flares are sudden, transient energy release above active regions of the Sun (Priest, 1982). The magnetic energy is released, and thus observed, in various form as thermal, soft and hard X-ray, accelerated particles etc. It seems natural to look for hints of flaring activity in the magnetic field in the photosphere, but the direct observation of the magnetic field itself gives no unambiguous results (e.g. Hagyard et al., 1999 and references therein). Recently, unambiguous observations of changing have been reported by Yurchyshyn et al. (2000). The authors observed some typical changes of the scaling behavior of the current helicity calculated inside an active region of the photosphere, connected to the eruption of big flares above that active region. In the present paper we conjecture that the changes in the scaling behavior of the observed quantity is related to the occurrence of changes in the topology of the magnetic field at the footpoint of the loop.

SIGNED MEASURE, CANCELLATIONS AND STRUCTURES

Topological properties of scalar fields which oscillate in sign can be studied through the scaling of signed measures. First of all, given a meanless, scalar field \( f(x) \), let us introduce the signed measure

\[
\mu_i(r) = \int_{Q_i(r)} f(x) \, dx
\]

through a coarse-graining of non overlapping boxes \( Q_i(r) \) of size \( r \), covering the whole field defined on a region of size \( L \). It has been observed (Ott et al., 1992) that, for fields presenting self-similarity, this quantity displays well defined scaling laws. That is, in a range of scales \( r \), the partition function \( \chi(r) \), defined as

\[
\chi(r) = \sum_{Q_i(r)} |\mu_i(r)| \sim r^{-\kappa}
\]

where the sum is extended over all boxes occurring at a given scale \( r \), follows a power-law behavior

\[
\chi(r) \sim r^{-\kappa}.
\]

The scaling exponent \( \kappa \) has been called cancellation exponent (Ott et al., 1992) because it represents a quantitative measure of the scaling behavior of imbalance between negative and positive contributions in the measure. For example, a positive definite measure or a smooth field have \( \kappa = 0 \), while \( \kappa = d/2 \) for a completely stochastic field in a \( d \)-dimensional space. As the cancellations between negative and positive part of the measure decreases toward smaller scales, we get \( \kappa > 0 \), and this is the interesting situation. It is clear that the presence of structures, seen as smooth parts of the field, has an important effect on the cancellation exponent. For example, values of \( \kappa < d/2 \), where \( d \) is the dimension of the...
space (in the present paper \( d = 2 \)), indicate the presence of sign-persistent \((i. e.\) smooth\) structures.

Within 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 \( \lambda \) be the typical correlation length of that structures, of the order of the Taylor microscale (see for example Frish, 1995), so that the field is smooth (correlated) in \( D \) dimensions with a cutoff scale \( \lambda \), and uncorrelated in the remaining \( d - D \) dimensions. If the field is homogeneous, the partition function (2) can be computed as \((L/\lambda)^d\) times the integral over a generic box \( Q(r) \) of size \( r \). The scaling of the latter can be estimated integrating over regular domains of size \( \lambda^d \) and considering separately the number of contributions coming from the correlated dimensions of the field and those from the uncorrelated ones. The integration of the field over the smooth dimensions will bring a contribution proportional to their area \((r/\lambda)^D\), while the uncorrelated dimensions will contribute as the integral of an uncorrelated field, that is proportional to the square root of their area /

\[
\kappa = (d - D)/2. \tag{4}
\]

**NUMERICAL SIMULATIONS**

Using high resolution numerical simulation of two-dimensional \((d = 2)\) turbulent magnetohydrodynamic flows (Politano et al., 1998; Sorriso-Valvo et al., 2000; Sorriso-Valvo et al., 2001), we can build up the signed measure for different fields. For example, since the geometry of the magnetic field \( B(x,y) = (B_x, B_y, 0) \) is two-dimensional, the current \( J(x,y) = \nabla \times B = (0,0,J_z) \) has only the \( z \) component, perpendicular to the 2-d simulation box, \( i. e. \) the plane \( (x,y) \). In Figure 1 we display the current field \( J(x,y) \) for the numerical data, using ten snapshots in the statistically steady state, from \( t = 168 \) up to \( t = 336 \) in non-linear times units, \( \tau_{NL} \). As can be seen, the presence of positive and negative structures is evident. The signed measure of the current can be then computed as

\[
\mu_t(r) = \int_{Q_t(r)} J_z(x,y) dx dy,
\]

and the scaling properties of the time averaged partition function are reported in Figure 2. A power-law scaling (3) is clearly visible in a range extending from the large scales (near the integral scale of the flow \( \ell_0 \approx 0.2L \), \( L = 2\pi \) being the size of the simulation box) down to a correlation length \( r^* \) of the order of the Taylor microscale \( \lambda \sim 0.02L \) of the flow (see for example Frish, 1995).

In this region, we fit the partition function to obtain 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 structures formation cascade, so that cancellations are stopped too. The fractal dimension of the current structures has been computed using the relation (4), which gives \( D \approx 1 \), indicating current structures similar to filaments. The presence of 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).

**SOLAR DATA**

To get a quantitative measure of the change of the scaling of current helicity inside active regions, 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 FeI 5324.19Å spectral line. The field of view is about \( 218'' \times 314'' \), corresponding to \( 512 \times 512 \) pixels on CCD. The magnetic field vector at the photosphere has been obtained through the measurements of the four Stokes parameters, and the current density \( J_z(x,y) \) has been calculated as a line integral of the transverse field vector over a closed contour of dimension \( 1.72'' \times 1.86'' \) (cf. Yurchishin et al., 2000, for details). The current helicity \( H_c = B \cdot J \) (where \( B \) represents the magnetic field and \( J = \nabla \times B \) the current density) is a measure of small scales activity in magnetic turbulence. It indicates the degree of clockwise or anti-clockwise knotness of the current density. Let us consider a magnetogram of size \( L \) taken on the solar photosphere of an active region, and let \( B_z(x,y) \) the observed magnetic field perpendicular to the line of sight \((x,y)\) are the coordinate on the surface of the sun). Through this field we can measure the surro-gate of current helicity, that is \( h_c(x,y) = B_z(x,y) J_z(x,y) \) being \( J_z(x,y) = \left| \nabla \times B_z \right| \hat{z} \). A signed measure can be defined from this quantity

\[
\mu_t(r) = \int_{Q_t(r)} h_c(x,y) dx dy. \tag{5}
\]

In Figure 3 we show, as example, the scaling behavior of \( \chi(r) \) vs. \( r \) for a flaring active region (NOAA 7315) which started to flare on October 22, 1992. At larger scales we find \( \chi(r) \sim \text{const.} \), and this is due to the complete balance between positive and negative contributions. The same behavior does not appear at smaller scales, showing that the resolution of the images is not high enough.
FIGURE 1. The current field $J$ obtained from high resolution two-dimensional numerical simulation of MHD equations. The different plots are ten snapshots in the statistically steady state, from about $t = 168$ up to $t = 336$ in non-linear times units, $\tau_{NL}$. As for the solar data, the presence of positive and negative structures on all scales is clear. We report, over each plot, the measured values of $\kappa$ and $D$.

FIGURE 2. The scaling of the partition function for the current obtained from numerical data. 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 $L = 2\pi$.

FIGURE 3. The scaling of the partition function for a flaring active regions (NOAA 7315), which started to flare on October 22, 1992. The power-law fit is indicated as a dotted line.

The value of $\kappa$ and then of $D$ through relation (4). Note that, since cancellations in the vertical photospheric magnetic field $B_z(x,y)$ itself have been found to be very small (Lawrence et al., 1993; Abramenko et al., 1998), with a cancellation exponent of the order of $10^{-2}$, cancellations of the current helicity are entirely due to the current structures.

In Figure 4, we report the time evolution of $D$ superimposed to the flares occurred in two active regions,
In this paper we point out that the changes in the scaling behavior of cancellations, measured through the cancel-
lation exponent $\kappa$, are due to the topology changes of the structures present in the field, and are thus related to the
importance of dissipative effects. The non-linear turbulent cascade, underlying the formation of such structures
on all scales, can be considered as a mechanism for flares. The results obtained from the analysis of the numerical simulations can be considered as a test for our model for the fractal dimension of structures, thus supporting our interpretation of the observational results for the photospheric magnetic field in the active regions.

To conclude, it is evident that the behavior we found can be used as a signature of the occurrence of big flares. High energy solar flares become of great interest because they can produce severe damages on Earth. Power blackouts, break up of communications and mainly damage of satellites or space flights, can be ascribed to energy released during big solar flares. It is then evident that the possibility of forecasting, even if partially, high energy flares has a wide practical interest to prevent the effects of flares on Earth and its environment. We build up a model which allows us to recognize without ambiguity changing behavior of the photospheric magnetic field of active regions. These changes, pointed out through the variation of a scaling index for current helicity, can be seen mainly before the eruption of big flares. The change of scaling index is due to the turbulent and intermittent energy cascade towards smaller scales, a mechanism which could be identified as the input of flaring activity, where energy is dissipated. The method could allow us to forecast, in real time, the appearance of the strongest flaring activity above active regions.

**REFERENCES**