Astron. Astrophys. 334, L57–L60 (1998)

ASTRONOMY AND ASTROPHYSICS

LETTER

Letter to the Editor

Does the photospheric current take part in the flaring process?

V.I. Abramenko[1], **V.B. Yurchishin**[1], **and V. Carbone**[2,3]

[1] Crimean Astrophysical Observatory, Nauchny, Ukraine
[2] Dipartimento di Fisica, Universitá della Calabria, I-87036 Roges di Rende, Italy
[3] Istituto Nazionale di Fisica per la Materia, Unitá di Cosenza, I-87036 Roges di Rende, Italy

Received 2 October 1997 / Accepted 17 March 1998

Abstract. On the basis of vector magnetograms of two flaring active regions (ARs) we analyze the scaling behavior of the current helicity H_c in the photosphere. The signed measure so obtained possesses a well pronounced sign–singularity in the range of scales from more than 10^4 Km down to the resolution limit of observations. We found that during the flaring process there is a signature both of a reorganization of the current helicity in the photosphere and of a strong magnetic energy dissipation of the photospheric magnetic field.

Key words: solar flares – scaling laws – turbulence

1. Introduction

Solar flares are phenomena of very fast magnetic energy release converted to solar plasma heating and particle acceleration (for a review see Priest, 1982). Usually solar flares are observed as a sudden, rapid and intense variation in brightness inside active magnetic regions between the upper chromosphere and the lower corona. For a long time solar flares were treated as a purely coronal phenomenon: a result of sudden energy release due to the reconnection in the current sheet (see for example the review by Somov, 1992). However recent observations of solar flares (Lu and Hamilton, 1991; Alikaeva et al., 1993; Lin et al., 1996) show that a solar flare is a phenomenon extending from the corona to the lower photosphere. The new viewpoint was first proposed by Parker (1987, 1988, 1989) and elaborated later by Lu and Hamilton (1991), Georgoulis and Vlahos (1996). According to Parker the principal cause of a solar flare should be *"the dissipation at the many tangential discontinuities arising spontaneously in the bipolar fields of the active regions of the Sun as a consequence of random continuous motion of the footpoints of the field in the photospheric convection"*. In other words, *"flares of all sizes are made up of clusters of nanoflares"* (Parker, 1988). If so, the strength of tangential discontinuities should be *"significantly reduced by the occurrence of the flare phenomenon"* (Parker, 1988). This should be most clearly visible in the value of the current and current helicity since tangential discontinuities arise most easily at the boundaries of opposite values of $\boldsymbol{B}$. One should observe changes in the characteristics of the spatial order of these values throughout the whole volume filled by nanoflares (and at the photosphere too).

In this letter we report observational evidences for the presence of a strong correlation between flares and the scaling laws of current helicity in the photosphere of ARs. This evidence is unambiguously related to the topological change of photospheric current which, in some form, must be taking part in the flaring process.

We analyze scaling properties both of the current helicity and the vertical magnetic field in active regions on the Sun. We used measurements of the magnetic field vector $\boldsymbol{B}$ obtained with the Solar Magnetic Field Telescope of the Beijing Astronomical Observatory (China). Measurements were recorded in the FeI 5324.19 Å spectral line. The field of view is about $218'' \times 314''$ (512×512 pixels of the CCD). Since we have information on $\boldsymbol{B}(x, y)$ only at one layer in the photosphere, we can calculate only a part of the photospheric current helicity:

$$H_c(x, y) = B_z \cdot (\boldsymbol{\nabla} \times \boldsymbol{B})_z \tag{1}$$

The data processing and the algorithm for H_c calculation are described in detail by Abramenko et al. (1996).

2. The cancellation exponent

The scaling properties of the cancellation between positive and negative contributions of an oscillating scalar field $F(x, y)$ can be analyzed by introducing a *signed measure* (Halmos, 1974)

$$\mu_i(r) = \int_{L_i(r)} F(x, y) dx\, dy \tag{2}$$

where $L_i(r) \subset L(R)$ represents a hierarchy of disjoint squares, of size r, covering the whole square L of size R which encloses the area of interest (throughout in the paper the field $F(x, y)$ is normalized to $\int_{L(R)} F(x, y) dxdy$). Then we can investigate the scaling behavior of the alternations in sign of the measure

Send offprint requests to: V. Carbone

by defining a scaling exponent κ through the expectation value of $|\mu_i(r)|$ at the scale r (Ott et al., 1992)

$$\chi(r) = \sum_{L_i(r)} |\mu_i(r)| \sim r^{-\kappa}, \tag{3}$$

(the sum is extended to all the squares of size r and the symbol $\sim$ means here that two quantities have the same scaling laws at least within a finite range of scales). Trivial values $\kappa = 0$ are obtained either if $\mu_i(r)$ is a probability measure ($\mu_i(r) > 0$ for all boxes $L_i(r)$), or if the signed measure has a smooth density (as $r \to 0$). In order to get $\kappa > 0$, the sum in (3) must increase as $r \to 0$, and this is true only if *the cancellations between positive and negative contributions in μ_i reduce as $r \to 0$*. When this is true the measure is said to be sign–singular and the scaling exponent κ is called *cancellation exponent*. Nontrivial examples of physical situations displaying this kind of singularity can be found in Ott et al. (1992), Bertozzi and Chhabra (1994), Vainshtein et al. (1994), Carbone and Bruno (1996, 1997).

As a rough estimate the current density at the scale r can be written in terms of the differences of the transverse magnetic field at two positions $j_z \sim \delta b_\perp(r)/r$, where $\delta b_\perp(r) = B_\perp(\boldsymbol{x}+\boldsymbol{r}) - B_\perp(\boldsymbol{x})$, so that, for the current helicity we obtain $\chi(r) \sim r^{-1} < \delta b_\perp B_z >$ (brackets being averages at the scale r). Assuming that the vertical magnetic field is only weakly statistically correlated to the transverse field differences, from Eq. (3) we get

$$\chi(r) \sim r^{-1-\phi} < \delta b_\perp > .$$

where ϕ is the cancellation exponent for the vertical magnetic field

$$\sum_{L_i(r)} \left| \int_{L_i(r)} B_z(x,y)dxdy \right| \sim r^{-\phi}$$

By introducing a scaling exponent ξ_1 for the first–order structure function of the transverse magnetic field, defined through $< \delta b_\perp > \sim r^{\xi_1}$ and related to the multifractal properties of fully developed turbulence (Frisch, 1995), we finally obtain the relation

$$\kappa \simeq 1 + \phi - \xi_1 \tag{4}$$

From data we can measure the values of κ and ϕ, then using expression (4) we can obtain a rough estimate for the scaling laws of the transverse magnetic field.

3. Data analysis

By looking at the fields $H_c(x,y)$ and $B_z(x,y)$, we calculate the signed measures $\mu_i(r)$ for both fields. Let us briefly describe how we get an estimate for the cancellation exponents in AR's, more details can be found in Yurchishin (1998) (see also Abramenko et al., 1998). We analyze boxes with sizes ranging from $R = 126$ pixels to $R = 48$ pixels (R being the largest scale), and let the scale r be measured in pixels in terms of R. We obtain the signed measure through (3), then we choose the linear interval in the plots of $\log \chi(r)$ vs. $\log(r/R)$, and finally the

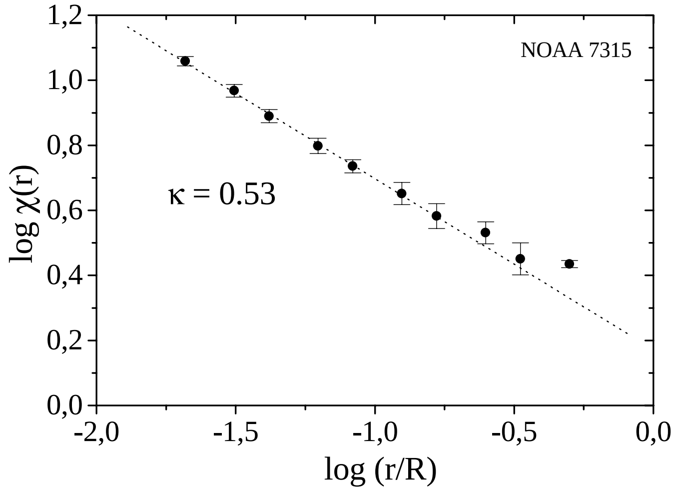

Fig. 1. We show the behavior of $\log \chi(r)$ vs. $\log(r/R)$ for the current helicity calculated through the magnetogram at UT 03:30 for AR NOAA 7315.

cancellation exponent was calculated as the linear best fit. For a given magnetogram we calculated the cancellation coefficient by choosing N different boxes of size R covering a given area. The choice is made in such a way that the boundary of the box does not cross the main maxima of the field H_c. Besides, quiet areas outside the spot should be minimally included in the box. Inside the m–th box ($m = 1, \ldots, N$), the function $\chi(r)$ was calculated, as well as the scaling exponent κ_m. Finally for each AR the average cancellation exponent $\kappa = \sum_m \kappa_m / N$, and their r.m.s. deviation, were calculated as a characteristic of each AR.

As an example of the sign–singular behavior, in Fig. 1 we plot $\log \chi(r)$ vs. $\log(r/R)$ (calculated for the current helicity) for the AR NOAA 7315 using the vector magnetogram at UT 03:32 20 Oct 1992. The sign–singularity described above is evident. In fact a linear behavior is visible in the range of scales from more than 10^4 Km, down to the resolution limits of observations (see also Abramenko et al., 1998). In Table 1 we report both the cancellation exponents κ and ϕ as calculated from two flaring ARs, namely NOAA 7585 and NOAA 7315.

We compared the changes in the cancellation exponent κ for current helicity with the variations of the flare activity in both ARs. Flare data where taken by the Solar Geophysical Data (N584 Pt. II, N595 Pt. II). All flares reported there within the time periods under consideration, are taken into account and presented in Figs. 2 and 3. In these figures we show the time evolution of the cancellation exponent κ calculated through the current helicity H_c obtained in some magnetograms. In both ARs we see a similar interesting situation: *before and after the big flares the value of κ is almost the same, but the periods of enhanced flaring activity are accompanied by a significant decrease of κ*. The effect is visible more clearly in the inserted figures, where a detail of the process in both ARs is shown. For example in AR NOAA 7315 (insert in Fig. 2) the first and the second magnetograms were recorded at 00:50 – 00:54 UT, and at 01:04 – 01:07 UT of 23 October 1992 respectively. We

Table 1. Cancellation exponents κ and ϕ for the studied active regions.

NOAA	Date	UT	κ	ϕ
7315	Oct 19,92	01:17	0.51 ± 0.05	0.062 ± 0.006
		02:00	0.48 ± 0.07	0.056 ± 0.001
		04:07	0.48 ± 0.06	0.049 ± 0.002
	Oct 20,92	01:40	0.52 ± 0.05	0.044 ± 0.002
		02:37	0.48 ± 0.04	0.040 ± 0.003
		03:32	0.52 ± 0.03	0.044 ± 0.002
	Oct 22,92	02:00	0.52 ± 0.02	0.031 ± 0.001
	Oct 23,92	00:50	0.49 ± 0.04	0.033 ± 0.001
		01:04	0.38 ± 0.03	0.033 ± 0.0005
		03:06	0.31 ± 0.03	0.031 ± 0.0005
	Oct 24,92	01:30	0.30 ± 0.04	0.034 ± 0.0004
		02:43	0.33 ± 0.06	0.033 ± 0.0004
		05:04	0.45 ± 0.06	0.033 ± 0.0005
7585	Sep 24,93	02:07	0.56 ± 0.03	0.068 ± 0.004
		06:00	0.35 ± 0.03	0.054 ± 0.002
		06:13	0.35 ± 0.02	0.052 ± 0.002
		07:04	0.43 ± 0.01	0.059 ± 0.001
		08:27	0.52 ± 0.01	0.057 ± 0.001
	Sep 25,93	03:45	0.46 ± 0.03	0.037 ± 0.002
	Sep 26,93	02:57	0.54 ± 0.03	0.035 ± 0.001

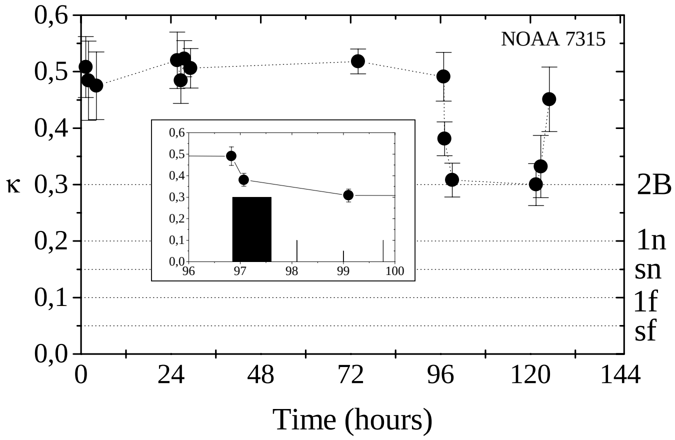

Fig. 2. We show the time evolution of the cancellation exponent κ for the current helicity in the AR NOAA 7585 (black symbols). In the same plot, as vertical lines we report all the flares observed in that AR. The amplitude of each vertical line corresponds to the intensity of the flare (in arbitrary units), according to the usual terminology. In the insert we report a fragment of the flaring process showing the details of the large 2B flare.

note the very sharp decrease of the value of κ from $\kappa \simeq 0.49$ up to $\kappa \simeq 0.38$, while at about 00:52 UT the large 2B (M4.1) flare started with the maximum at about 00:59 UT. Looking at the cancellation exponent for B_z, we found $\phi \ll 1$ (see Table 1), in agreement with previous investigations (Lawrence et al., 1993). In particular ϕ is an order of magnitude less than κ. Then, according to relation (4), the sum between κ and ξ_1 is roughly constant. This implies that κ and ξ_1 follow an opposite behavior: a decrease of κ is accompained by an enhancement of ξ_1 and *vice versa*.

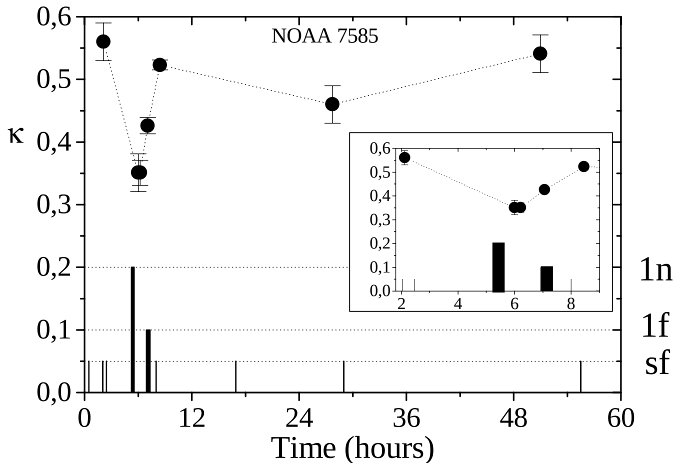

Fig. 3. The same as Fig. 2 for the AR NOAA 7315. In the insert we show the details of both the $1n$ and $1f$ flares.

Since κ abruptly decreases, our results indicate that cancellations between negative and positive contributions reduce in a drastic way, and at the same time the flare starts to brighten. This implies that during the flare a reorganization of the current helicity occurs in the photosphere. From the point of view of the photospheric current helicity the flare is then seen as a drastic annihilation of small scales. In fact during the flare the value of ξ_1 increases abruptly and this is a signature that magnetic energy of the transverse field at the photosphere has been released in a very short time. From the point of view of the turbulent energy cascade the spectral magnetic energy density $E(k)$ at wave vectors $k \sim 1/r$ behaves as $E(k) \sim k^{-1-2\xi_1}$. For example the $5/3$–Kolmogorov spectrum corresponds to $\xi_1 = 1/3$ or the $3/2$–Kraichnan spectrum corresponds to $\xi_1 = 1/4$. In general, due to intermittency, ξ_1 is different from both values (Frisch, 1995; Carbone et al., 1995). If ξ_1 increases, the energy spectrum becomes steeper, and this physically corresponds to a situation where a big quantity of energy has been transferred to high wavevectors into the dissipative domain.

A different signature of energy annihilation can be seen by looking at the total fluxes for the magnetic field $\Phi(B_z) = (1/R^2)\sum |B_z|$ and for the current helicity $\Phi(H_c) = (1/R^2)\sum |H_c|$. We calculated these quantities for the magnetograms of October 23, 1992 at times 00:50, 01:04 and 03:06. While $\Phi(B_z)$ at both 01:04 and 03:06 decays to 0.94 times the value at 00:50, the total helicity decays respectively to 0.79 times and 0.64 times the value at 00:50. This is to say that only the photospheric current decayed during the flare.

4. Conclusions

In summary the picture of flare which emerges from our observations is not very different from the classical picture (Priest, 1982): we found experimental signatures for magnetic energy release and rapid reorganization of large–scale structures. However our main result is the fact that the cancellation exponent we studied is obtained through the current helicity in the photosphere (1). Since the cancellation exponent for B_z is very small (see also Lawrence et al., 1993), the observed strong variations in the values of κ are caused mainly by the photospheric current $(\boldsymbol{\nabla} \times \boldsymbol{B})_z$. Therefore the strong correlation between κ and the flare activity of an AR means that the strength of tangential discontinuities of the transverse photospheric magnetic field is significantly reduced by a flare, which supports Parker's idea about the principal cause of a solar flare (Parker, 1987). The result obtained suggests that with the flare onset over the whole volume from corona to photosphere the evolved magnetic field is active through many very small reconection events.

Acknowledgements. Part of this work was supported by the Italian Ministero della Universitá e della Ricerca Scientifica.

References

Abramenko V.I., Wang T., & Yurchishin V.B. 1996, Sol. Phys. 168, 75
Abramenko V.I., Yurchishin V.B., & Carbone V. 1998, Sol. Phys. 178, 35
Alikaeva K.V., Kondrashova N.N., Redyuk T.I., & Rudnikova E.G. 1993, Kinematic and Physics of Celestial Bodies 9, 57
Bertozzi A., & Chhabra A.B.: 1994, Phys. Rev. E 49, 4716
Carbone V., & Bruno R.: 1996, Ann. Geophys. 14, 777
Carbone V. & Bruno R.: 1997, ApJ 488, 482
Carbone V., Bruno R., & Veltri P.: 1995, Phys. Rev. Lett. 75, 3110
Frisch U.: 1995, Turbulence: the legacy of A.N. Kolmogorov, Cambridge University Press
Georgoulis M.K., & Vlahos L. 1996, ApJ 469, L135
Halmos P.R.: 1974, Measure Theory, Springer–Verlag, New York
Lawrence J.K., Ruzmaikin A.A., & Cadavid A.C. 1993, ApJ 417, 805
Lin Y.–Z., Zhang H.–Q., & Zhang W.–J. 1996, Sol. Phys. 168, 135
Lu E.T., & Hamilton R.J. 1991, ApJ 380, L89
Ott E., Du Y., Sreenivasan K.R., Juneja A., & Suri A.K.: 1992, Phys. Rev. Lett. 69, 2654
Parker E.N. 1987, Sol. Phys. 111, 297
Parker E.N. 1988, ApJ 330, 474
Parker E.N. 1989, Sol. Phys. 121, 271
Priest E.: 1982, Solar Magnetohydrodynamics, D. Reidel Publishing Company, Dordrecht
Somov B.V. 1992, Physical Processes in Solar Flares, Kluwer Academic Publishers, Dordrecht
Vainshtein S.I., Sreenivasan K.R., Pierrhumbert R.T., Kashyap V., & Juneja A.: 1994, Phys. Rev. E 50, 1823
Yurchishin V.B. 1998, PhD thesis (in Russian)