SPATIOTEMPORAL ORGANIZATION OF ENERGY RELEASE EVENTS IN THE QUIET SOLAR CORONA

VADIM M. URITSKY and JOSEPH M. DAVILA

1 Catholic University of America at NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA; vadim.uritsky@nasa.gov
2 NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA

Received 2014 May 23; accepted 2014 August 19; published 2014 October 9

ABSTRACT

Using data from the STEREO and SOHO spacecraft, we show that temporal organization of energy release events in the quiet solar corona is close to random, in contrast to the clustered behavior of flaring times in solar active regions. The locations of the quiet-Sun events follow the meso- and supergranulation pattern of the underlying photosphere. Together with earlier reports of the scale-free event size statistics, our findings suggest that quiet solar regions responsible for bulk coronal heating operate in a driven self-organized critical state, possibly involving long-range Alfvénic interactions.

Key words: instabilities – Sun: activity – Sun: corona – Sun: flares – Sun: magnetic fields

Online-only material: color figures

1. INTRODUCTION

The Sun’s corona has arguably one of the most violent plasma environments in the solar system accessible to observation. Coronal active regions formed by an intense large-scale magnetic convection in the underlying photosphere produce major explosive events such as X-class flares, coronal mass ejections, and filament eruptions causing dramatic space weather effects. Quiet coronal regions dominated by the magnetic network exhibit smaller-scale but abundant energy release events which are instrumental for bulk coronal heating (see, e.g., Karpel et al. 1995; Aschwanden 2006; Solanki et al. 2006; Antiochos et al. 2007 and references therein). Understanding the physical mechanism responsible for heating the corona via these bursty events remains one of the most important problems in astrophysics (Klimchuk 2006).

The directly measured coronal brightenings are unable to supply the energy loss rates of $10^5$–$10^7$ erg cm$^{-2}$ s$^{-1}$ required for the coronal heating (Athay 1966). This discrepancy implies a collective contribution from a large number of partially unresolved energy release events such as those associated with a localized magnetic reconnection (López Fuentes & Klimchuk 2010) or resonant wave heating (Ofman et al. 1998). The appearance of such events in the topologically complex and highly conductive coronal plasma involves cooperative interactions across wide ranges of spatial, temporal, and energy scales (McAteer et al. 2005, 2010; Uritsky et al. 2013).

Self-organized criticality (SOC; Bak et al. 1987, 1988) and fluid turbulence (Monin & Yaglom 1975) are two plausible statistical-physical scenarios governing multiscale interactions in the corona. SOC models address the thermodynamic limit of Parker’s scenario of nanoflare heating (Parker 1983, 1988) under slow-driving conditions (Lu & Hamilton 1991; Charbonneau et al. 2001) and reproduce many of the observed coronal statistics (Charbonneau et al. 2001; Uritsky et al. 2013). High-Reynolds number fluid turbulence in coronal loops (e.g., Nigro et al. 2004; Buchlin & Velli 2007) offers an alternative path to these probabilistic signatures.

The two scenarios can be distinguished based on the statistics of occurrence times of dissipation events (Boffetta et al. 1999; Lepreti et al. 2001). In paradigmatic SOC models, the times of initiation of energy avalanches are fully random since the probability of an avalanche is given by the ratio between the number of minimally stable states and the total system size (Bak et al. 1987). As the latter increases, this ratio approaches a constant, giving rise to Poisson statistics of the event occurrence times. In intermittent turbulence, the occurrence times are organized in multiscale clusters revealing the hierarchy of temporal scales of the underlying fluid dynamics (Boffetta et al. 1999). While the temporal clustering of energy dissipation is not necessarily related to turbulent flows (Sánchez et al. 2002; Paczuski et al. 2005; Wheatland 2000), its absence makes a strong case for an SOC-like dissipation mechanism.

Until now, analyses of temporal correlations of solar flares have been focused on high-energy eruptive events resulting in significant increases of the extreme ultraviolet or X-ray emission fluxes (Boffetta et al. 1999). Such events are typically produced by solar active regions (Wheatland 2000; Török et al. 2011) and do not reflect the dynamics of bulk coronal plasma residing in the quiet regions.

In this paper, we present the first statistical study of the occurrence times of heating events in the quiet Sun in conjunction with spatial clustering of the events. Using the correlation integral (CI) technique, we show that temporal organization of these events is indistinguishable from a stationary Poisson process across the entire observed range of scales ($300$–$5 \times 10^4$ s), and is therefore consistent with paradigmatic SOC models. Clustering of event positions follows the convection pattern of the photospheric supergranulation acting as a spatially distributed driver. Together with earlier reports of power-law distributions of heating events, our results suggest that bulk energy conversion in the solar atmosphere occurs via SOC-like avalanches of magnetic energy dissipation, possibly involving long-range Alfvénic interactions.

2. DATA AND METHODS

We studied coronal images obtained from the Solar Terrestrial Relations Observatory Extreme Ultraviolet Imager (STEREO EUVI; Scherrer et al. 1995) during 17:29:00 05/04/2007–10:58:00 06/04/2001. The interval of observations provides a representative example of the dynamics of a quiet Sun for which prolonged high-cadence EUVI data were available. The overall activity level during the observed interval
remained low, with the GOES X-ray fluxes staying below $10^{-8}$ W m$^{-2}$. The 171Å bandpass corresponding to Fe IX and Fe X emission lines was used, with the maximum response at the solar plasma temperature $\sim 9 \times 10^5$ K. We also analyzed a set of Solar and Heliospheric Observatory Michelson Doppler Imager (SOHO MDI; Scherrer et al. 1995) magnetograms co-aligned with the STEREO EUVI images. Both image sets were de-rotated and rebinned to a spatial resolution of 0.6 arcsec, with an average sampling time of 66.1 s. The smallest spatial scale addressed by our analysis exceeds the native resolution of the EUVI images by a factor of $\sim 2$ ensuring that the results are insensitive to the rebinning procedure. The obtained data cubes contained 770 $\times$ 500 $\times$ 952 points in the latitudinal, longitudinal, and temporal directions, correspondingly. The field of view was close to the disk center ensuring small projection distortions.

Figure 1(a) shows a sample STEREO EUVI image combined with isolines (shown in black) of the unsigned line-of-sight SOHO MDI magnetic flux in the studied solar region. The observed fragmented magnetic carpet and sparse coronal emission pattern are typical of a quiet Sun (Leighton et al. 1962; Hагенаар et al. 1997; Shine et al. 2000; Rieutord & Rincon 2010). Some of the bright coronal locations coincide with magnetic field reversals, as expected for the quiet-Sun magnetic network (see, e.g., Falconer et al. 1998), and could be sites of low-altitude magnetic reconnection (Kарpen et al. 1995).

The inter-event time of flaring events in the quiet solar corona is typically shorter than the event duration (Uritsky et al. 2013). Multiple events developing at different locations can overlap in time, and their proper analysis requires spatiotemporal (Berger & Title 1996), as opposed to time-series based (Boffetta et al. 1999; Paczuski et al. 2005), detection techniques. Our detection method (Uritsky et al. 2002, 2007, 2010) identifies image features staying for more than one sampling interval above a specified detection threshold and occupying separable sub-volumes in the three-dimensional (3D) spacetime.

The first step of the applied feature-tracking technique consists of building a table of contiguous time intervals called activations where the local values of the studied data field exceeds the detection threshold (Uritsky et al. 2010). Next, we labeled spatially connected clusters of activations using the “breadth-first search” principle to avoid backtrack of search trees. All 26 nearest neighbors in the 3D spacetime, including the diagonal neighbors, were considered to identify the connected clusters which were treated as individual solar events. The detection thresholds were adjusted to represent comparable levels of intermittency in the studied image sets (Uritsky et al. 2013), yielding 4124 coronal and 5912 photospheric events (Figure 1(b)). The results reported below for these sets of events also have been reproduced for several other combinations of thresholds. The occurrence time $t$ of every event was measured using two alternative methods: based on the event onset time $t_1$ or its average time $(t_1 + t_2)/2$, where $t_1$ ($t_2$) is the time of the first (last) image containing the event. We also recorded the average starting heliographic position $r = (x, y)$ of each detected event.

Due to a high average occurrence rate of coronal events (more than four events per sampling interval), their temporal clustering could not be tested using inter-event time distributions (Boffetta et al. 1999; Lepreti et al. 2001). Instead, we applied the CI technique (Grassberger & Procaccia 1983) based on the analysis of second-order moments of the multifractal expansion of a clustered stochastic set (Grassberger 1983; Schuster & Wolfram 2005). The CI characterizes the probability of finding a pair of data points within a hypersphere of a specified radius $\epsilon$ representing in our case temporal interval $\tau$ or spatial distance $r$, and is estimated by the sum

$$C_{XY}(\epsilon) = K_{XY} \sum_{\xi_X \in X} \sum_{\xi_Y \in Y} \Theta(\epsilon - \|\xi_X - \xi_Y\|)$$

where $X, Y \in \{H, M\}$ are sets of heating ($H$) or magnetic ($M$) events, $\xi_{X,Y}$ are the occurrence times or the positions of the events in these sets, $K_{XY}$ is the normalization constant ensuring $C_{XY}(\epsilon) \rightarrow 1$ as $\epsilon$ reaches the largest observed scale, and $\Theta$ is the Heaviside step function. The combinations $\epsilon = \tau$, $\xi = t$ and $\epsilon = r$, $\xi = r$ define respectively temporal and spatial CI. If the sets $X$ and $Y$ are identical, Equation (1) describes auto-correlations between the events (Grassberger & Procaccia 1983). For a self-similar clustered set $X$ of occurrence times and positions, $C_{XX}(\tau) \sim \tau^\beta$ and $C_{XX}(r) \sim r^\alpha$, with $\beta \leq 1$ and $\alpha \leq 2$. The special cases $\beta = 1$, $\alpha = 2$ refer to the scaling of fully uncorrelated sets of events governed by the embedding dimension $d$ of the analysis domain. If the sets $X$ and $Y$ are distinct, the correlation dimensions characterize the closeness of two fractal measures (Kantz 1994), with $\beta > 1$ ($\beta < 1$) and $\alpha > 2$ ($\alpha < 2$) signaling negative (positive) cross-correlations in temporal and spatial domains, correspondingly (Uritsky & Davila 2012).
in the absence of correlations. The insets show the dependence of local magnetic events in the quiet Sun. Dotted lines represent log–log slopes expected analysis of temporal (a) and spatial (b) clustering of heating and photospheric events. The power-law slope of \( C_{HH} \) clustering condition between the two. Temporal CIs are in agreement with the non-power-law scaling behavior intrinsic to the solar structure and dynamics. We performed a calibration based on a synthetic set of events characterized by fully random timings and positions subject to the same observational constraints as the solar events. The CI \( \hat{C}(r) \) of this random set of events is described by \( g = 1 \) and \( D = d \), allowing us to introduce the corrected correlation dimensions

\[
D^*(\epsilon) = -\frac{\delta \log [C(\epsilon)/\hat{C}(\epsilon)]}{\delta \log \epsilon} + d = D + \delta D(\epsilon),
\]

in which \( \delta D = \partial \log g(\epsilon)/\partial \log \epsilon \) and \( D^* \in (\beta^*, \alpha^*) \). By design, \( D^* \) is independent of the observational distortions and approaches \( D \) over a scaling range where \( g \) is constant.

Figure 3 displays the corrected dimensions \( \beta^* \) and \( \alpha^* \) estimated using Equation (2) and plotted as a function of \( \tau \) and \( r \) scales. The average values and the standard errors of the corrected dimensions are provided in Table 1. The data show that the temporal dimension is indistinguishable from the random prediction for \( \tau \sim 3 \times 10^4 \text{ s} \). Within this range, the dynamics of the studied solar region are adequately described by the stationary Poisson process, in contrast to the active Sun showing fractal clustering of flaring times over approximately the same range of scales (Aschwanden & McIntier 2010). The corrected spatial dimensions (1) are consistently below the value of 2 over the range of scales controlled by meso- and supergranulation (up to \( r \sim 20 \text{ Mm} \)). The leading role of instrument resolution and the largest observable \( \tau \) and \( r \) values imposed by the size of the image and the duration of the image sequence. To eliminate these artifacts, we used the scaling ansatz

\[
C(\epsilon) = \epsilon^D f(\epsilon) g(\epsilon),
\]

where \( \epsilon \) is the scale of interest, \( D \) is the corresponding correlation dimension, \( f(\epsilon) \) is the cutoff function representing observational distortions, and \( g(\epsilon) \) accounts for a non-power-law scaling behavior intrinsic to the solar structure and dynamics.
the photosphere in the emergence of this spatial structure is manifested in its systematically lower $\epsilon^*$ values (Figure 3). The spatial cross-correlation dimension suggests that the positions of the coronal brightenings are arranged in a multiscale pattern which is consistent with the multiscale organization of the quiet Sun magnetic network (Rast 2003; Uritsky & Davila 2012). The multiscale co-alignment of the two event sets can be also seen in Figure 1(b).

The absence of ensemble-averaged statistical correlations between the event timings leaves a possibility of a more subtle temporal organization associated with the presence of so-called sympathetic coronal eruptions (Török et al. 2011) triggering secondary instabilities via magnetohydrodynamic (MHD) waves. We tested this scenario using a causal network approach. Each coronal event was considered as a node of a directed graph. Outgoing links are added between a given event and all other events occurred within a 5 minute interval after that event, excluding the events described by a zero time lag. The links could represent causal connections between the events resulting in their nearly-simultaneous occurrence, but they can also be random. The Erdős–Rényi random graph model (Erdős & Rényi 1959) predicts that in the latter case, the degree distribution $p(k)$ describing the probability of finding a node with $k$ incoming or outgoing links follows a binomial distribution which converges to a Poisson distribution for large $N$: $p(k) \approx e^{-\lambda} (\lambda^k)/k!$, where $\lambda$ is the average number of links per node (Erdős & Rényi 1959; Gilbert 1959; Albert & Barabasi 2002).

The out-degree distribution of the photospheric graph is fairly close to the purely random case, but the coronal graph shows a pronounced departure from the Poisson law for $k \gtrsim 25$ (Figure 4) where the number of outgoing links is systematically larger compared to the random graph. These network hubs have no effect on the CI shape as they account for less than 3% of the total population of events, but they can be quite important as triggers of secondary heating activity. Sympathetic events in solar active regions have been considered in the context of expanding flux ropes working as MHD triggers of a second generation of reconnection events (Török et al. 2011). Our analysis speaks in favor of such remote interactions in the quiet corona.

We found that the average transverse coronal length of the outgoing links attached to highly-connected events characterized by the condition $k \gtrsim 25$ is $160 \pm 30$ Mm. This distance is traveled in $\lesssim 300$ s, implying a communication speed of $500$ km s$^{-1}$ or faster. The provided estimate is consistent with the Alfvén speeds in the corona measured using coronal magnetography (Brosius et al. 1997) and other remote techniques (see, e.g., Warmuth & Mann 2005 and references therein).

4. CONCLUSIONS

Together with the power-law distribution of event sizes published previously (Uritsky et al. 2013), our findings indicate that the bulk heating of the corona can be controlled by SOC-like avalanches of energy dissipation (Bak et al. 1987; Lu & Hamilton 1991) up to timescales comparable to the lifetime of supergranulation cells (Rieutord & Rincon 2010).

The preferred locations of heating events are preconditioned by the nonuniform distribution of free magnetic energy supplied by the photosphere (Falconer et al. 1998). However, the moments at which the stored energy is released are likely to be determined by local instability conditions rather than the large-scale energy supply, and are essentially random. A more coherent energy dissipation associated with turbulent plasma heating (see, e.g., Buchlin & Velli 2007) could, in principle, occur at $\sim 10^5$ s timescales not properly resolved in this study.

Finally, the causal network analysis performed suggests that bulk coronal heating is, at least partially, a nonlocal phenomenon which may involve long-distance Alfvénic interactions between remote coronal regions. This non-locality could play a significant part in triggering secondary instabilities in the quiet corona and must be addressed in future models of coronal heating.

We acknowledge J. Klimchuk, A. Pulkkinen, and J. Guerra for helpful discussions and A. Coyner for preparing solar images. The work of V.U. was supported by NASA grant NNG11PL10A 670.002 to CUA/IACS.

REFERENCES

Albert, R., & Barabasi, A. L. 2002, RvMP, 74, 47
Antiochos, S. K., DeVore, C. R., Karpen, J. T., & Mikic, Z. 2007, ApJ, 671, 936
Aschwanden, M. J. 2006, Physics of the Solar Corona (Berlin: Springer)
Aschwanden, M. J., & McTiernan, J. M. 2010, ApJ, 717, 683
Athay, R. G. 1966, ApJ, 146, 223
Bak, P., Tang, C., & Wiesenfeld, K. 1987, PhRvL, 59, 381
Bak, P. T., C., & Wiesenfeld, K. 1988, PhRvA, 38, 364
Berger, T. E., & Title, A. M. 1996, ApJ, 463, 365
Boffetta, G., Carbone, V., Giuliani, P., Veltri, P., & Vulpiani, A. 1999, PhRvL, 83, 4662
Brosius, J. W., Davila, J. M., Thomas, R. J., & White, S. M. 1997, ApJ, 488, 488
Buchlin, E., & Velli, M. 2007, ApJ, 662, 701
Charbonneau, P., McIntosh, S. W., Liu, H. L., & Bogdan, T. J. 2001, SoPh, 203, 321
Erdős, P., & Rényi, A. 1959, Publ. Math. (Debrecen), 6, 290
Falconer, D. A., Moore, R. L., Porter, J. G., & Hathaway, D. H. 1998, ApJ, 501, 386
Gilbert, E. N. 1959, Ann. Math. Stat., 30, 1141
Grassberger, P. 1983, PhLA, 97, 227
Grassberger, P., & Procaccia, I. 1983, PhyD, 9, 189
Hagenaar, H. J., Schrijver, C. J., & Title, A. M. 1995, ApJ, 481, 988
Kantz, H. 1994, PhRvE, 49, 5091
Karpen, J. T., Antiochos, S. K., & Devore, C. R. 1995, ApJ, 450, 422
Klimchuk, J. A. 2006, SoPh, 234, 41

Figure 4. Out-degree distributions of the causal networks describing solar photosphere and corona. Thin lines surrounding each distribution show histogram errors at the level of three standard deviations. Dotted lines are the Poisson fits corresponding to the Erdős–Rényi random graph model using the provided average numbers of links of heating ($k_H$) and magnetic ($k_M$) events. (A color version of this figure is available in the online journal.)
Leighton, R. B., Noyes, R. W., & Simon, G. W. 1962, ApJ, 135, 474
Lepreti, F., Carbone, V., & Veltri, P. 2001, ApJL, 555, L133
López Fuentes, M. C., & Klimchuk, J. A. 2010, ApJ, 719, 591
Lu, E. T., & Hamilton, R. J. 1991, ApJL, 380, L89
McAteer, R. T. J., Gallagher, P. T., & Conlon, P. A. 2010, AdSpR, 45, 1067
McAteer, R. T. J., Gallagher, P. T., & Ireland, J. 2005, ApJ, 631, 628
Monin, A. S., & Yaglom, A. M. 1975, Statistical Fluid Mechanics: Mechanics of Turbulence (Vol. 2, Cambridge, MA: MIT Press)
Nigro, G., Malara, F., Carbone, V., & Veltri, P. 2004, PhRvL, 92, 194501
Ofman, L., Klimchuk, J. A., & Davila, J. M. 1998, ApJ, 493, 474
Paczuski, M., Boettcher, S., & Baines, M. 2005, PhRvL, 95, 181102
Parker, E. N. 1983, ApJ, 264, 642
Parker, E. N. 1988, ApJ, 330, 474
Rast, M. P. 2003, ApJ, 597, 1200
Rieutord, M., & Rincon, F. 2010, LRSP, 7, 2
Sánchez, R., Newman, D. E., & Carreras, B. A. 2002, PhRvL, 88, 068302
Scherrer, P. H., Bogart, R. S., Bush, R. I., et al. 1995, SoPh, 162, 129
Schuster, H. G., & Wolfram, J. 2005, Deterministic Chaos: An Introduction (Weinheim: Wiley-VCH)
Shine, R. A., Simon, G. W., & Hurlburt, N. E. 2000, SoPh, 193, 313
Solanki, S. K., Inhester, B., & Schussler, M. 2006, RPPh, 69, 563
Török, T., Pasanenko, O., Titov, V. S., et al. 2011, ApJL, 739, L63
Uritsky, V. M., & Davila, J. M. 2012, ApJ, 748, 60
Uritsky, V. M., Davila, J. M., Ofman, L., & Coyner, A. J. 2013, ApJ, 769, 62
Uritsky, V. M., Klimas, A. J., Vassiliadis, D., Chua, D., & Parks, G. 2002, JGR, 107, 1426
Uritsky, V. M., Paczuski, M., Davila, J. M., & Jones, S. I. 2007, PhRvL, 99, 025001
Uritsky, V. M., Pouquet, A., Rosenberg, D., Mininni, P. D., & Donovan, E. F. 2010, PhRvE, 82, 056326
Warmuth, A., & Mann, G. 2005, A&A, 435, 1123
Welsch, B. T. 2006, ApJ, 638, 1101
Wheatland, M. S. 2000, ApJL, 536, L109