SPATIAL AND TEMPORAL DISTRIBUTION OF ENERGETIC PHENOMENA ON THE SUN

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ABSTRACT/RESUME

The sun exhibits transient, large scale, energetic phenomena, namely solar flares, coronal mass ejections etc, directly affecting the space environment and the earth. The location and rate of appearance of these phenomena follow the general solar cycle, however there is a significant random component in their emergence. Also, the evolution and interactions between close magnetic structures of the sun is complicated and not a well understood process. We study the spatial and temporal distributions of transient energetic phenomena of the sun, investigating possible correlations and organization over wide range of scales. We also address the evolution of the distributions of energetic solar phenomena throughout the solar cycle.

1. INTRODUCTION

While the details of individual energetic solar phenomena include complex and only partly understood MHD processes, the overall statistical description of their occurrence may follow universal laws also describing systems of completely different dynamics yet also characterized by intermittent, and to some extend unpredictable bursts the system observables (e.g. 1/f noise, catastrophic events, evolution in biological systems, zip's law in linguistics, commodity prices etc).

Self-organized criticality (SOC) appears a suitable scenario for generating intermittency through complexity [1,2]. In the SOC paradigm of sand pile model periods of stasis are interrupted by intermittent sand slides, or avalanches (a domino effect) and the number of avalanches N(s) of size, s, is given by power law distribution $N(s)=s^{-a}$, where, a, is the power-law exponent, characteristic of the particular physical process (often close to unity). Power-law size distributions can be reproduced computationally as the output of *cellular automata models*, in which energy is added, cascaded and released as a collective phenomenon on a grid. Indeed power-law distributions are ubiquitous in wide range of physically different intermittent systems. In geophysics, the earthquakes exhibit power-law distributions in both magnitude (Gutenberg-Richter law, [3]) and occurrence time [4]. This power-law size distribution of earthquake magnitudes can be explained as due to a spatially self-similar, fractal distribution of seismic volumes on the earth's crust, and the distribution of occurrence as due to long-range correlated fractal clustering of seismic events in time [5]. In astrophysics, the distribution of magnitude of sudden changes in pulsar rotation rate [6] and the material drift in the disk surrounding black holes [7] were proposed being SOC phenomena.

Solar flares are eruptive events releasing at short time immense amounts of magnetic energy previously stored in the magnetic structure's topology through a, not well-understood, reconnection mechanism. It was proposed that flares represent the dissipation at the many tangential discontinuities arising on the bipolar fields of an active region of the sun as a consequence of random continuous motion of the footprints of the field in the photospheric convection [8,9]. Lu and Hamilton [10] constructed a simple theory of the solar flare occurrence, based on the hypothesis that the solar corona is in a meta-stable SOC state. In the relative cellular automata models, able to reproduce the power law behavior in the distribution functions of the total energy, the peak luminosity and the duration of the flares [11], the magnetic energy is added into a 3D grid and avalanches of flare clusters takes place. Indeed, in analogy with the Gutenberg-Richter law for the earthquake magnitudes [12], the probability distributions, calculated for various flare related quantities, are found to be well represented, at least for wide range of sizes, as being power law [13], with exponents 1.7 for the distribution of the X-ray emission peak flux, 1.5 for the total energy associated, with, and 2.3 for the flare duration [14,15,16]. Studies of the hard X-ray flare catalogues (HXR) revealed power law distributions not only for the energy, time duration and peak value of the events but also for the waiting intervals between successive events [17,18,19], with exponents 2.38 ± 0.03 for flares in the same active region, and 2.4 ± 0.1 for all the flares regardless their position, also verified by MHD turbulence cell models leading to 2.05 for the peak distribution, 1.8 for the total energy distribution, 2.2 for the bursts duration and 2.7 for the waiting time between successive events [20,21].

2. DATA ANALYSIS AND RESULTS

In this presentation we used the catalogue of soft X-ray events recorded by GOES satellite, for the years 9/1/1975-1/31/2002. We only used events with recorded time of start, end and maximum from a certified active region. Since the data cover more than one solar cycle (in particular cycles 21, 22 and partly 23) we also consider distributions as functions of time, to study their dependence on the to the cycle's phase.

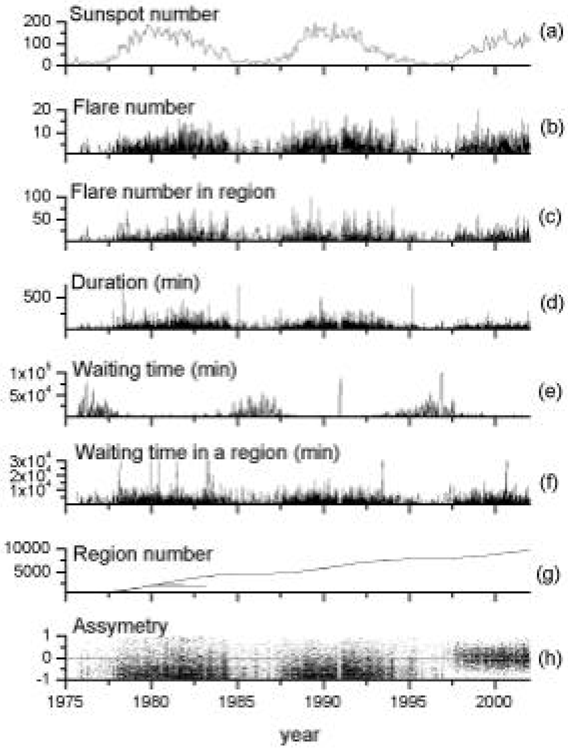

Fig 1: The temporal evolution of the soft X-ray event parameters

As shown in figure 1, the sunspot number, 1(a), is positively correlated with the daily number of events, 1(b), the number of events in an active region 1(c), the event duration, 1(d), and the waiting time between events within the same region, 1(f), while is anti-correlated with the waiting time between events regardless of region, 1(e). Therefore, at minimum the total event rate is reduced. However within the same region, (and since the event duration is a measure of the event's magnitude), at cycle's minimum smaller events occur and more frequently, while at maximum large events occur but with reduced frequency.

The plot of active region number as a function of time, 1(g), shows that active regions are produced with enhanced rate during the solar maximum, while with significantly reduced rate at the raise and decline cycle phase. Therefore, the rate of active region production also follows (is actually a smoothed version of) the overall solar cycle. The time asymmetry of each flare event, 1(h), defined as the different between raise and decay time of flux, normalized to the duration of the event, shows that the events of cycles 21 and 22 were significantly *time-asymmetric*, while of 23 mostly *time-symmetric*. Note that the solar cycles 21 and 22 themselves were also of relatively large amplitudes, hence more asymmetric (Welmeier effect), as compared to cycle 23, which is expected to be more symmetric since of medium amplitude. Possibly this result indicates that the time-asymmetry of each flare event reflects the asymmetry of the overall solar cycle that it occurs.

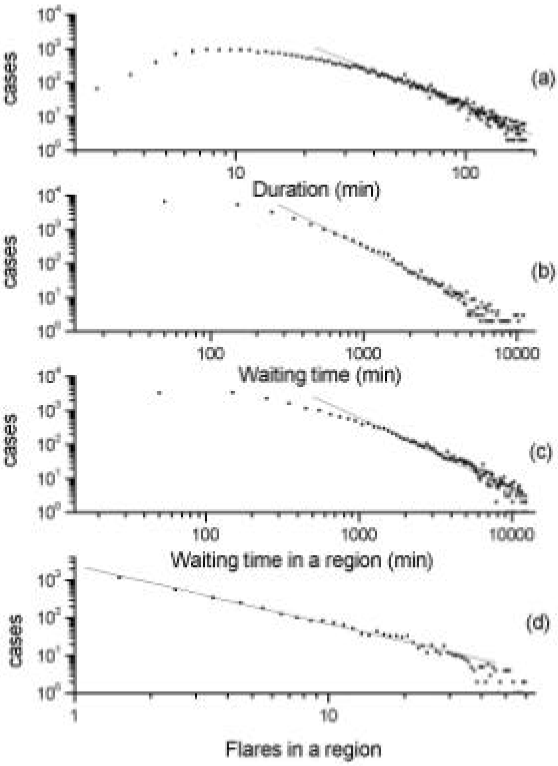

Fig 2: The distributions of event duration and waiting times of the soft X-ray events.

The distributions of event duration (fig. 2(a)), waiting times between successive events in all, 2(b) and in each region, 2(c), and number of events occurring in the same region, 2(d) exhibit power-law tails. The most probable event duration, as shown in fig. 2(a), is 10 minutes. The corresponding power law exponents (also depending on the selected range for linear fitting) were found 2.72 ± 0.06 for the duration, 2.26 ± 0.05 for the waiting time between events, 2.01 ± 0.07 for the waiting time within each region (which are in general agreement with the previously estimated exponents for the hard X-rays, [14,15,16,20,21]) and 1.58 ± 0.04 for the number of flares occurring in each region. The duration and the waiting time distributions also posses segments significantly departing from a power-law distribution at short timescales. Partly responsible for these deviations are observational catalogue errors in the determination of start, end and maximum times (each of the order of 1 min). However in these deviations may also be hidden a not exactly self-similar hierarchical organization that remains to be understood. The distribution of event durations also reflects the wide range of energy releases in the flare emissions. The non-Poisson, power-law distributions of the waiting time between successive events provide evidence that the individual flare events are not mutually uncorrelated, but hierarchically clustered in time. Indeed such long range time correlations are expected since the active regions are magnetically connected and the occurrence of flares causes a drastic redistribution of the magnetic energy and alter of the magnetic topology, thus e.g. affecting the lifetime of nearby magnetic structures and triggering new flare events at close or even large distances.

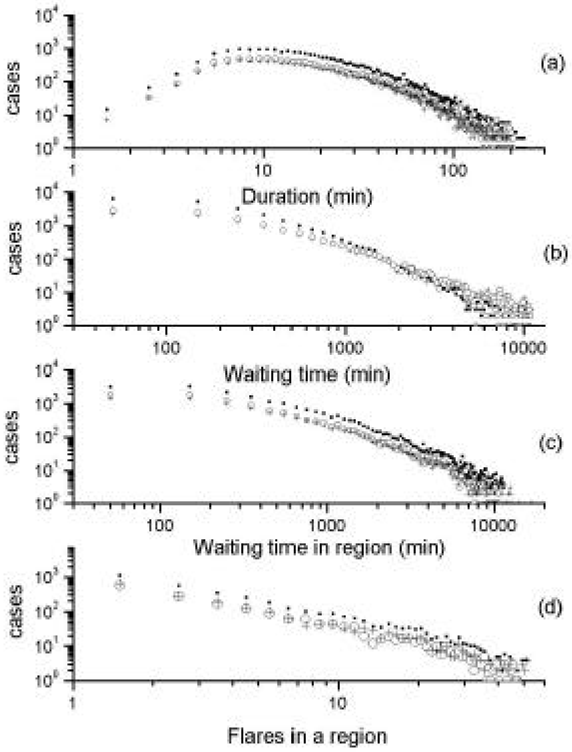

Fig 3: The distributions of event duration and waiting times for both hemispheres (full dots), north semi sphere (open triangles) and south semi sphere (crosses).

We also considered the distributions of duration and waiting times separately for the north and south solar semi sphere in order to detect possible asymmetries As we conclude from figure 3, there is no statistically significant difference in the distribution shapes and therefore the power-law exponents, in both and each semi sphere separately.

The spatial distribution of successive events on the solar disk was also studied, deriving the distribution of angular separation of pairs of temporally successive events.

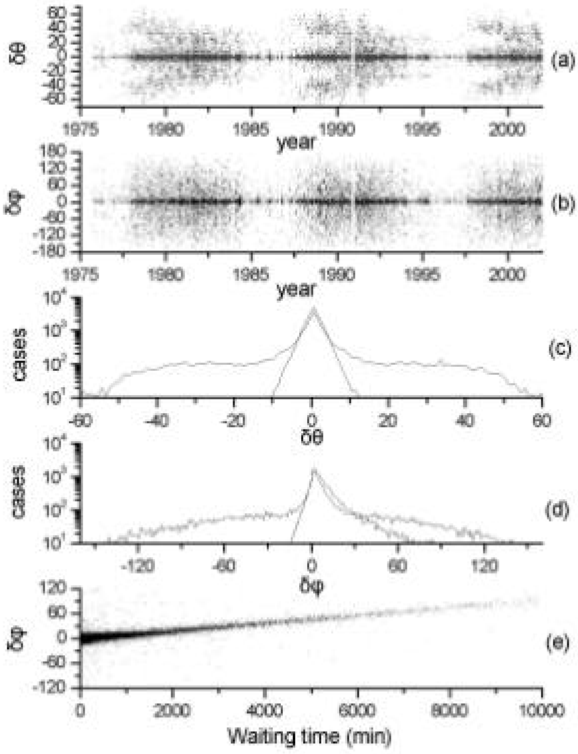

Fig 4: The distributions of angles of (a) latitudal and (b) longitudal separation between successive events. Inner curves concern events in the same active region. (c) The longitudal angular separation as function of temporal separation (waiting time) between events.

The latitude separation (fig. 4(a)) evolves in as a butterfly diagram (since the second member of the pair occurs in latitude given by the well-known butterfly diagram) plus a distribution of events from the same active region, while the longitude separation remains nearly the same throughout each cycle. As shown in fig. 4(c), 4(d), most of the pairs of successive events happen again in the same active region, with exponentially decaying probability distribution. The distribution of separation in longitude is asymmetric because of the solar differential rotation, as also can be seen in fig. 4(c): the slope is 360 degrees/27 days (the means solar rotation angular velocity). Pairs of events happening in different active regions differ in distributions, being nearly uniformly distributed in latitude (corresponding to the butterfly distribution of events) and Gaussian-distributed in longitude. No significant north-south asymmetry in the angular separation distributions (not shown) was detected.

3. CONCLUSIONS

We analyzed the soft X-ray flare catalogue of events recorded by GOES satellite for the years 1975-2002. The main conclusions are:

(a) The daily number of soft X-ray events, number of events in each active region, event duration and waiting time between events within the same region follow (i.e. are positively correlated to) the overall solar cycle variations, while the waiting time between events regardless of active region is anti-correlated to the solar cycle.

(b) The events were statistically time-asymmetric, with raise time to maximum flux less than decay time, during the relatively large-amplitude (hence more asymmetric) solar cycles 21 and 22 while more time-symmetric during the raising phase of medium-amplitude (hence more symmetric) cycle 23, possibly indicating a relation between each event time asymmetry and the overall asymmetry of the 11-year cycle.

(c) The distributions of event duration, waiting time between successive events (overall and within each region) and number of events occurring within an active region exhibit power-law segments for a wide range of scales. The power law exponents found are 2.72 ± 0.06 for the duration, 2.26 ± 0.05 for the waiting time between events, 2.01 ± 0.07 for the waiting time within each region. The power-law distribution of duration (indicative also of the event magnitude) is expected from both the hypothesis about a meta-stable, self-organized (SOC) state of the solar corona and analogy with Guttenberg-Richter law of seismology. The existence of power-law distributions of waiting times over wide range of timescales imply that the events are long-range correlated in time, i.e. each event triggers others in its vicinity or even at large distances, due to the spatial interconnection of the erupting magnetic structures. No statistically significant north-south asymmetry could be detected in the distributions.

(d) The study of the spatial (angular) separation between successive events showed that most events happen again in the same active region with exponentially decaying probability distributions, while events occurring at different regions occur with butterfly-like evolving uniform angular distribution in latitude and Gaussian in longitude.

REFERENCES

1. Bak, P., Tang, C., Wiesenfield, K., Phys. Rev. Lett., 59, 381, 1987
2. Bak, P.: How nature works, the science of self-organized criticality, Copernicus, Springer-Verlag, New York, 1996.
3. Gutenberg, B., Richter, C.F., Seismicity of the Earth and associated phenomenon, 2nd Edition, Princeton University Press, Princeton, 1954.
4. Omori, F., Rep. Inv. Commun.2, 103,1984
5. Turcotte, D.L., Fractals and chaos in geology and geophysics, Cambridge University Press, p. 35-71, 1992.
6. Cheng, B., Epstein, R.I., Cuyer, R. A., Young, C., Nature, 382, 518-520, 1996.
7. Mineshige, S., Takeuchi, M., Nishimoti, H., APJ, 435, L. 125, 1994.
8. Parker, E. N., Astrophys. J,.330, 474, 1988
9. Parker, E. N., Sol. Phys., 121, 271, 1989.
10. Lu. E., Hamilton, R., Astrophys.J., 380, L89, 1991.
11. Georgoulis, M .K., Vlahos, L., Astron. Astrophys., 336, 721, 1998.
12. Bak, P., Christensen, K., Dannon, L., Scanlon, T.: American Geophysical Union, Spring Meeting, SP51C-01, 2001.
13. Temmer, M., Veronig, A., Hanslmeier, A., Otruba, W., Messeroti, M., Astron. Astrophys., 375, 1049-1061, 2001.
14. Lin, R. P., Schwarz, R. A., Kane, S. R., Pelling, R. M., Hurley, K. C., Astrophys.J 283,421, 1984.
15. Sturrock, S., Kaufmann, P., Moore, P. L., Smith, D. F., Sol. Phys. 94,341, 1984.
16. Crosby, N. B., Aschwanden, M. J., Dennis, B. R., Sol.Phys.143, 275, 1993.
17. Pearce, G., Rowe, A., Yeung, J., Astrophys..Space Sci. 208,99, 1993.
18. Crosby, N., Vilmer, N., Lund, N., Sunyaev, R., Astron.Astrophys.334, 299,1 998.
19. Wheatland, M. S., Sturrock, P. A., McTiernan, J. M., Astrophys.J.509,448,1998.
20. Boffetta, G., Carbone, V., Giuliani, P., Veltri, P., Vulpiani, A., Phys. Rev. Lett. 83, 4662 1999.
21. Giuliani, P., Carbone, V., Veltri, P., Boffetta, G., Vulpiani, A., Physica A 280, 75-80, 2000.