Part 1. Solar Drivers and Activity Levels

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Statistical Analysis of Individual Solar Active Regions

Garyfallia Kromyda[1] **and Loukas Vlahos**[2]

[1]Department of Physics, Aristotle University of Thessaloniki GR-52124 Thessaloniki, Greece
email: glkromyda@gmail.com

[2]Department of Physics, Aristotle University of Thessaloniki GR-52124 Thessaloniki, Greece
email: vlahos@astro.auth.gr

Abstract. In the last decades, numerous observational and computational studies have shown that the global flare distribution is a power-law with a slope less than 2. In these studies, active regions are treated as statistically indistinguishable. To test this, we identify and separately analyze the flares produced by ten individual active regions (2006-2016). In five regions, we find a single power-law distribution, with a slope of $a < 2$. In the other five, we find a broken double power-law distribution, with slopes $a_1 < 2$ and $a_2 > 2$.

Keywords. Sun: corona, flares, X-rays, radiation mechanisms: thermal, methods: statistical, data analysis

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1. Introduction

A possible coronal heating scenario was proposed by Parker (1988). Parker envisioned a corona full of magnetic flux tubes of all sizes, where small reconnection events are happening along each flux tube at a high occurrence rate. These small events release energy on the order of $10^{20} - 10^{24}$ erg and are called nano-flares. The energy released heats the corona, which radiates some of this energy away, predominantly in soft X-rays. The solar X-ray flare distribution follows a power-law form:

$$f(E) = f_o E^{-\alpha}, \quad \alpha > 0 \tag{1.1}$$

where $f(E)dE$ is the fraction of flares releasing an amount of energy between E and $E + dE$ per unit time. As shown in Hudson (1991) the total energy released per unit time by the ensemble of flares is:

$$E_{tot} = \int_{E_{min}}^{E_{max}} f(E) E dE = f_o \left[\frac{E^{2-\alpha}}{2-\alpha}\right]_{E_{min}}^{E_{max}}, \quad \alpha \neq 2 \tag{1.2}$$

- If $\alpha < 2$: the larger flares of the distribution are the source of coronal heating.
- If $\alpha > 2$: nanoflares are the source of energy for the corona.

Up to today, all observational studies have found distributions with slopes $1.7 < \alpha < 1.9$, contrary to what Parker's nano-flare heating theory would require.

The theory that is able to explain the power-law flare distribution is Self-Organized Criticality, pioneered by Bak *et al.* (1987, 1988), and adapted to solar flares by Lu & Hamilton (1991) and Lu *et al.* (1993) (see recent review by Aschwanden *et al.* 2016). An active region is treated as a system of energy storing nodes which are driven slowly (the energy injection rate is much slower than the energy release rate) and weakly (the amounts of energy injected into the system are much smaller than the amounts stored at any node) and exchange energy with each other. If the value at a node exceeds a critical

Active Region	Activity Period	# AR flares all flares	# X	# M	# C	# B	q-values
10848	14 - 29/1/2006	83/99	-	-	7	75	0.84
10930	3 - 18/12/2006	167/183	4	5	46	112	0.91
10960	31/5 - 13/6/2007	102/125	-	10	16	76	0.82
10963	7 - 18/7/2007	79/94	-	-	18	61	0.84
10978	3 - 19/12/2007	79/119	-	-	9	66	0.66
11029	24/10 - 1/11/2009	64/71	-	-	9	53	0.90
11158	11 - 21/2/2011	82/124	1	7	65	9	0.66
11271	13 - 30/8/2011	76/130	-	-	11	65	0.58
12192	14 - 31/10/2014	134/144	6	34	94	-	0.93
12529	4 - 21/4/2016	78/88	-	1	30	47	0.89

Figure 1. The selected active regions of this study

threshold, an instability able to also destabilize neighboring nodes sets in, and energy is released, known as an avalanche. The distribution of the magnitude of the avalanches for a system in the SOC state is a power-law. The avalanche time-series have a '1/f' power spectrum, with slopes between 1 and 3, indicative of long temporal correlations.

2. Data Collection

In this study we conduct a statistical analysis of the flares produced by 10 individual active regions, analyzing the flares of each active region separately. We search for active regions that produced more than 60 flares during their lifetime on the visible side of the Sun. To identify them we use the SolarSoft Latest Events Archive, where each flare record is assigned to an active region and is accompanied by a flare locator image. This search produced 10 active regions, shown in Figure 1. For each of these, we construct a flare-list, where each flare record has a start, stop and peak time, a position and a magnitude.

We start from the GOES soft X-ray time-series (long channel at $1 - 8\mathring{A}$ and short channel at $0.5 - 4\mathring{A}$), which show all flares irrespective of their active region origin. To construct time-series that show the flares of a single active region, we use the start, stop and peak times from the active region flarelist. We constructed an analysis algorithm in the IDL programming language that implements the following:

(a) Fills up data gaps in the observed time-series using interpolation of a linear model between the original flux value of the last point before the gap and the original flux value of first point after the gap. These gaps are not during flares. Their correction is necessary in order for the algorithm to correctly match times from the flare-lists to observations in the time-series.

(b) Corrects for duplicate flares (13 duplicate flares in total) by counting them only one time.

(c) If the start, stop and peak times from the flare-lists are plotted on the time-series, occasional discrepancies are revealed. The algorithm determines new start, stop and peak times for the flares, for the short and the long channel separately.

(d) Background subtraction for each flare (for the two channels separately). The algorithm:

- creates a background flux profile using the Wheatland (2010b) method.
- creates an alternative background flux profile by interpolating a linear fit between the flux at the start and the flux at the end of the flare.

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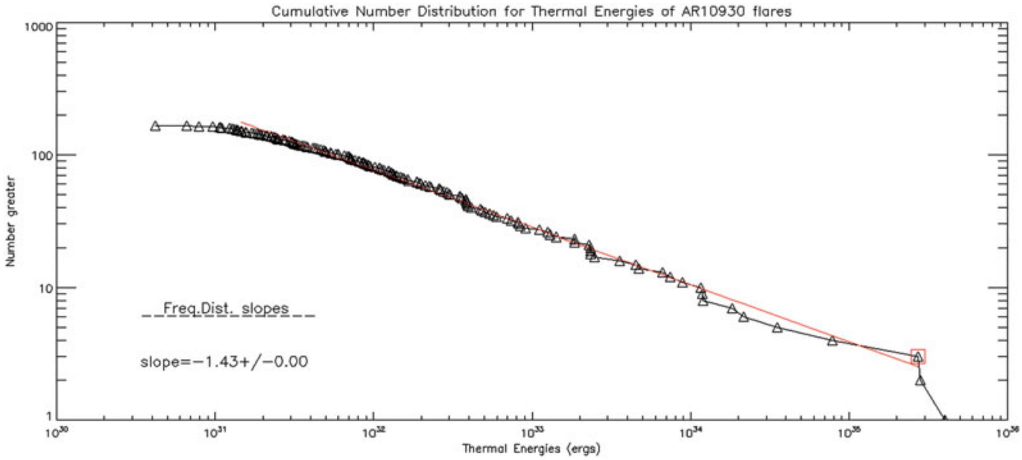

Figure 2. Cumulative Distribution of flare thermal energy events for active region 10930

- chooses the most appropriate background profile for each flare separately. This is the one that when subtracted, makes the peak flux of the flare profile greater. The two peak flux values do not differ by much, but using this criterion the most visually reasonable flare profile is chosen.

Using the two channels and the goes_chianti_tem SolarSoft routine, the temperature (T) and emission measure time-series (EM) corresponding to the flare timeseries are created. The thermal energy E acquired by plasma due to a flare can be found by assuming thermal equilibrium of a fully ionized hydrogen plasma, so that $E = 3kT\,\mathrm{EM}/n$. Using the calculated T and EM, and $n = 10^{10} cm^{-3}$, thermal energy time-series can be calculated.

3. Analysis and Results

Using the thermal energy time-series of each active region, and the thermal energy events corresponding to the region's flares, we construct cumulative distributions, as shown in Figure 2 and 3. For each energy value on the x-axis, the y-axis value corresponds to the number of flares with energy greater than the x-axis value.

For all 10 active regions (ARs), the powerlaw at the lowest energy limit, around 10^{31} erg, is less than 2, against what nano-flare heating requires. Furthermore, only half of the ARs show a single power-law. The other half show broken power-laws, with a first part having a slope less than 2, and a second part having a slope greater than 2. Only the single slope ARs can be considered true SOC systems. Their slope values are in agreement with the values predicted by Lu & Hamilton (1991). The double slope ARs cannot be considered true SOC systems. As a result we claim that the corona as a whole may be in a SOC state, but not all ARs can reach a SOC state during their flare-producting lifetime.

A possible explanation for broken power-laws is the existence of strong drivers, based on Georgoulis & Vlahos (1996) and Charbonneau (2001) simulations. According to Charbonneau (2001) strong drivers, where the energy injected at any time is comparable to the energy stored in system nodes, hinder the creation of large clusters. Thus scale-free, true SOC systems cannot exist, and mid-sized flares are favored, giving rise to broken power-laws. In the future, we plan to test the validity of the above claims, using Hinode vector magnetograms, since a magnetogram-driven simulation can clarify this point.

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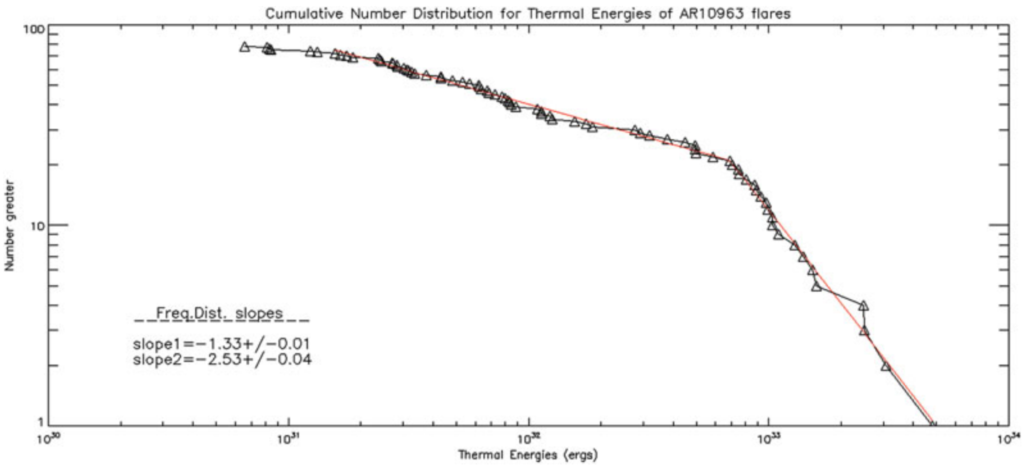

Figure 3. Cumulative Distribution of flare thermal energy events for active region 10963

No correlation is found in scatter plots of waiting time versus the energy of the previous or the following flare. Flares in individual ARs seem to be independent events in time. Such events have Poisson distributions, and their slopes in log-lin axis give us the average waiting time of the AR. This is inversely proportional to the average driving rate of the AR. We find one slow and one fast average waiting time, implying the existence of time-varying drivers in ARs. In general, the waiting time distributions are well-fitted by doublewise Poisson distributions.

The power spectrum of flare time-series of both channels sometimes show clear power-laws, other times show power-laws with fluctuations. The slopes average to 1.7. The auto-correlation functions (ACF) of the flare time-series show short correlation times. All these indicate that some type of self-organization exists in all ARs, but ARs are not typical SOC systems.

The power spectrum of background time-series of both channels (data points bewteen start and end of all flares in the original GOES timeseries are replaced with a linear fit between flux at start and flux at end of the flares) show clear powerlaws in all cases. The slopes average to 2.1. The ACFs of the background time-series show long correlation times. All these indicate that the background corona could be a SOC system in its own right, even though we cannot yet observationally identify the nano-flares it produces.

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