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Solar flares and thermal wind reversals: critical metastable states

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Abstract

Two data sets of metastable states duration time: one obtained in a laboratory thermal convection experiment and another in the satellite's Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI: 2002–2003 yy) observations, are compared in order to extract an information about a general (common) statistical mechanism in the onset of the metastable states. Simple probability distributions for both data sets show the same distinctive power-law (with exponent -1.1 ± 0.1) and the exponential tails. More sophisticated analysis with moving average moments reveals a specific critical-like clusterization of the data in the both data sets with remarkably close values of the exponents.

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Keywords: Solar flares; Critical metastable states

1. Introduction

Metastable large-scale states in turbulent thermal convection is one of the intriguing recent discoveries, which is now under active consideration both theoretically and experimentally. In a recent paper [1] properties of the abrupt reversal of the mean circular wind direction in turbulent thermal convection at high Rayleigh numbers are studied using the data obtained at laboratory conditions (measurements were made in a closed cylindrical container of aspect ratio 1, the working fluid was cryogenic helium gas). Using the data properties it is suggested that a stochastic "change of stability" between two metastable states with opposite circular wind direction takes place in this situation. The waiting times between the metastable states were short on the scale of the duration times, so the wind reversals were abrupt. The last property most likely is a consequence of the specific boundary conditions of the experiment, while the observed statistical properties of

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the duration times indicate a general dynamic mechanism similar to the self-organized criticality (SOC) [1,2]. Self-organized criticality occurs through a nonlinear feedback mechanism triggering transitions between different metastable states. These transitions take the form of intermittent avalanchelike events distributed according to a power law. There could be many possible scenarios of SOC in this complex system where numerous plumes and jets are developed as a result of boundary layer instabilities, all of which are embedded in a background of strong turbulent fluctuations prevalent in the core. It was suggested recently for plasma turbulence by [3,4] that instabilities governed by a threshold may lead to self-organized criticality by producing transport events at all scales (avalanches). These avalanches are due to local accumulation of energy, leading to an increasing gradient. Once the gradient exceeds the threshold, a burst of activity occurs, which expels the accumulated energy. This process can be renewed, much like a domino effect, leading to a large transport event. Specific conditions of the thermal convection in the container, in particular the basic symmetry in respect of the wind rotation direction, make these states metastable and cause the random wind reversals. Supposed general character of this mechanisms stimulates us to seek for others laboratory and natural phenomena with metastable states which exhibit analogous statistical properties of the duration times. One of such phenomena is solar flare. The solar flares are the manifestation of a sudden, intense and spatially concentrated release of energy in the solar corona. According to the Parker's idea [5] stochastic photospheric fluid motions shuffle the footpoints of magnetic coronal loops. The high electrical conductivity of the coronal gas implies that the magnetic field is frozen-in, so that the subsequent dynamical relaxation within the loop results in a complex, tangled magnetic field, essentially force-free everywhere except in numerous small electrical sheets which form spontaneously in highly-stressed regions. As the current within these sheets is driven beyond some threshold, reconnection sets in and releases magnetic energy, leading to localized heating. The authors of [6] suggested that SOC could describe the main features of the hard X-ray flares with avalanches of the reconnection events as the flares (see for further development [7–9] and references therein).

2. Probability distributions

Figs. 1, 2 show probability density functions calculated for the duration times of the thermal wind metastable states and of the solar flares respectively. The solar flares duration times used in present Letter were recently measured by RHESSI (The Reuven Ramaty High-Energy Solar Spectroscopic Imager, NASA), between 12 February 2002 and 15 April 2003. The data set contains about 8000 detected flares. The similarity between Figs. 1 and 2 seems to be remarkable. Especially, it is appearance of the distinctive

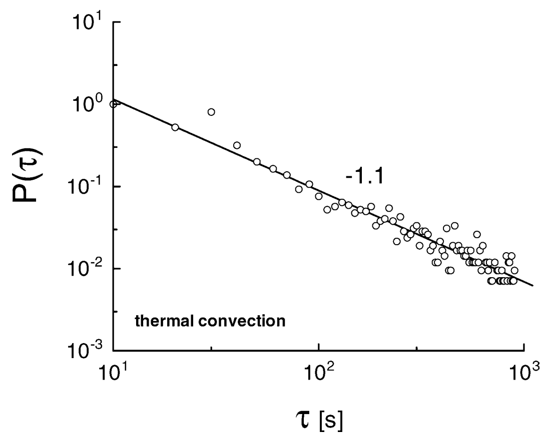

Fig. 1. Logarithm of probability density function, $P(\tau)$, of the duration times against logarithm τ for the thermal convection metastable states (circular wind). The straight line is drawn in order to indicate power-law dependence $P(\tau) \sim \tau^{-\gamma}$ ($\gamma = 1.1 \pm 0.1$).

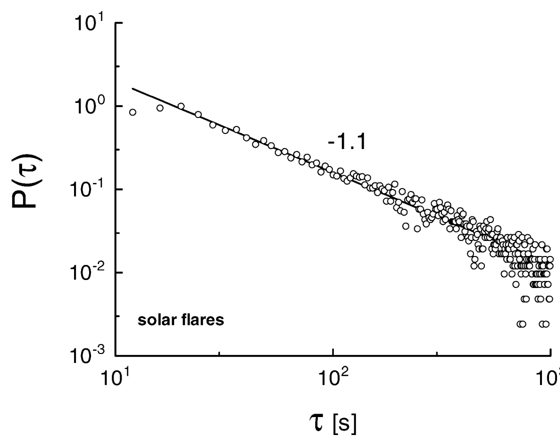

Fig. 2. As in Fig. 1, but for the RHESSI solar flares duration times.

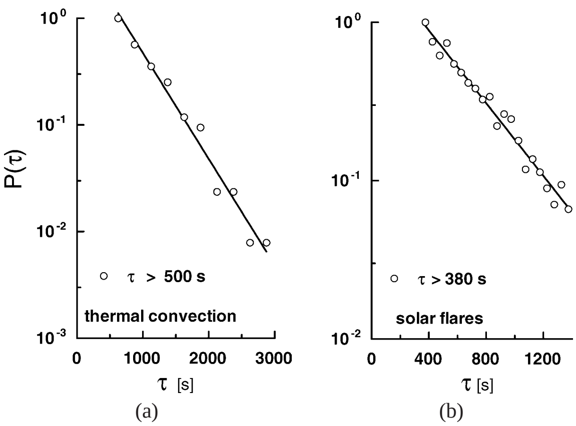

Fig. 3. Logarithm of probability density function, $P(\tau)$, of the large duration times against τ for the thermal convection. The straight line is drawn in order to indicate the exponential dependence (2); (b) as in (a) but for the RHESSI solar flares large duration times.

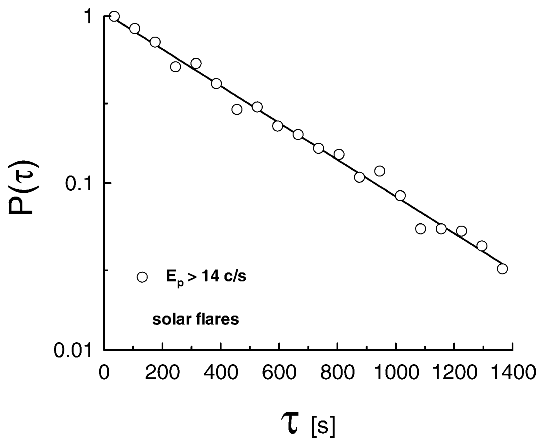

Fig. 4. Logarithm of probability density function, $P(\tau)$, of the duration times against τ for the RHESSI solar flares duration times at the condition: $E_p > 14$ c/s. The straight line is drawn in order to indicate the exponential dependence (2).

power law:

$$P(\tau) \sim \tau^{-\gamma}, \quad \gamma = 1.1 \pm 0.1 \tag{1}$$

which is shown in the figures as a straight line (in log–log scales).

It should be noted that the power-law distribution function with the exponent $\gamma \simeq 1.1$ has been already mentioned by [10] for hard X-ray flares duration times observed in the WATCH/GRANAT satellite experiment.

Now, let us look at the large τ tails of these distributions. Fig. 3(a), (b) show (in semi-logarithmical scales) these tails for the thermal convection and for the flares respectively. In both cases the data indicate exponential tails

$$P(\tau) \sim e^{-\tau/\tau_0} \tag{2}$$

(the straight lines in the figures).

One can consider appearance of these tails as a consequence of a finite-size phenomenon

$$P(\tau) \sim \tau^{-\gamma} e^{-\tau/\tau_0}. \tag{3}$$

But the flares data allow us to show that situation is more complex. Indeed, the flares are also characterized by their peak count rate E_p. We decided to separate the flares with "large" E_p and to study probability distribution of their duration times (this data set consists of about a half of the total number of observed flares).

Fig. 4 shows probability density function of the duration times calculated for this data subset. The straight line in this figure indicates exponential distribution (in the semi-logarithmical scales). Despite the starting point of the observed in Fig. 4 exponential distribution is $\tau = 30$ s (i.e., vary far from the tail values (cf. Fig. 3), the characteristic time $\tau_0 \simeq 390$ s for this distribution is about the same as that extracted from the tail distribution (i.e., from the slope in Fig. 3(b)). Of course, this phenomenon might be related to the fact that statistically the flares with large E_p have larger duration times than those with small E_p (e.g., *average* duration time for flares with $E_p \leqslant 14$ c/s is 88 seconds while for those with $E_p > 14$ c/s the average duration time is 457 seconds). However, this is already an intrinsic physical phenomenon.

3. Moments

The simple probability density functions give only very general information about the statistical processes. In particular, probability density function gives no information about statistical relations between neighboring events (clusterization). To extract such information from the data we use moving average moments. A measure based on the duration time can be introduced as following

$$\tau_r = \frac{1}{r} \sum_{i=n}^{i=n+r-1} \tau(i), \tag{4}$$

where duration time $\tau(i)$ has the number i in a given data set. This measure is a moving average of duration times and can be useful for investigation of the events clusterization if the data set has a physically meaning order. Let us recall ([11]) that in the case of critical phenomena like percolation or liquid–gas transition the moments

$$M_p = \sum_s s^p P(s, \alpha) \tag{5}$$

of the cluster size, s, distribution with $p > 1$ diverge at the critical point in the thermodynamic limit

$$M_p \sim |\alpha|^{-\mu_p}, \tag{6}$$

where α denotes the distance from the critical point, (order parameter), i.e., $\alpha = p - p_c$ for percolation or $\alpha = T - T_c$ for the liquid–gas transition.

Clusterization in a duration times data set should result in a qualitative gap between probability density function for the individual duration time: $P(\tau = \tau_1)$, and probability density functions for the moving average (4): $P(\tau_r)$. Therefore, for clusterization in the data set one can use as an order parameter $\alpha = r - 1$. Then critical-like clusterization should result in equation

$$\langle \tau_r^p \rangle \sim |\alpha|^{-\mu_p} \tag{7}$$

with the order parameter $\alpha = r - 1$ (cf. Eq. (6)). To illustrate the situation for the real data sets we present in Fig. 5 normalized second moments for the duration times in the convection wind (circles) and for the Poissonian case of solar flares with $E_p > 14\ c/\mathrm{s}$ (crosses). The critical-like representation (7) has no particular physical meaning and we suggest it as an approximation, which can be useful to identify (see last paragraph in the section) and to analyze the clusterization phenomenon.

Fig. 6(a) shows logarithm of the moments $\langle \tau_r^p \rangle$ against $\ln\alpha$ (with $\alpha = r - 1$) for the thermal convection experiment. The straight lines (the best fit) are drawn in order to indicate the multiscaling (7). Fig. 6(b) shows results of analogous calculations for the RHESSI data set.

Fig. 7 shows the exponents μ_p (7) extracted as slopes from Fig. 6(a) (triangles) and from Fig. 6(b) (circles). One can see that this comparison also indicates similarity between the two data sets, now on the cluster level.

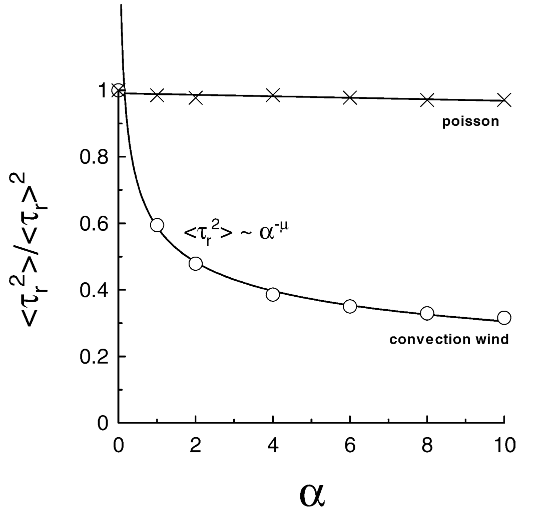

Fig. 5. Normalized second moments for the convection wind (circles) and for the Poissonian case of solar flares with $E_p > 14\ c/\mathrm{s}$. The solid curve corresponds to the critical-like dependence (7).

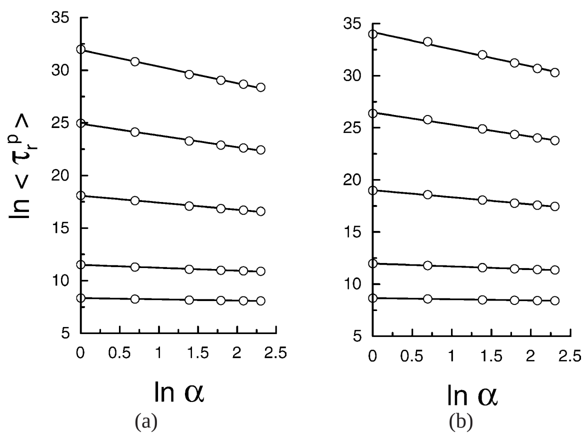

Fig. 6. Logarithm of the moments $\langle \tau_r^p \rangle$ against $\ln\alpha$ (with $\alpha = r - 1$) (a) for the thermal convection experiment, and (b) as in Fig. 6(a), but for the RHESSI data set of the solar flares duration time. The straight lines (the best fit) are drawn in order to indicate the multiscaling (7).

For the Poissonian distribution the clusterization phenomenon is obviously absent. Therefore, for this distribution $\mu_p = 0$ for all p. For the flares with large peaks ($E_p > 14\ c/\mathrm{s}$) we observe Poissonian distribution of the duration times (see Fig. 4). Therefore, we can use the "high intensity" flares subset ($E_p > 14\ c/\mathrm{s}$) to check relevance of the multiscaling (7) for detecting of the clusterization phenomenon. The exponents μ_p calculated for this subset are shown in Fig. 7

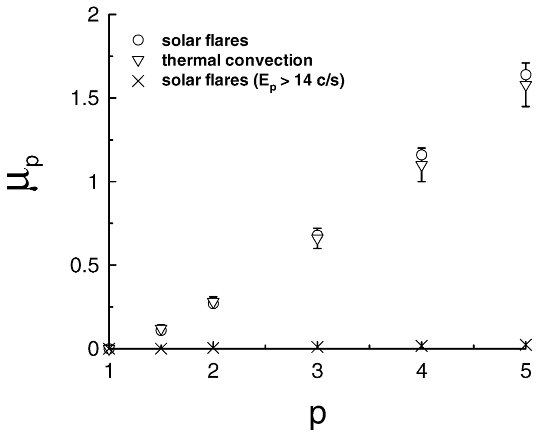

Fig. 7. The exponents μ_p (7) extracted as slopes from Fig. 6(a) (triangles) and from Fig. 6(b) (circles) for the thermal convection experiment and for the RHESSI data set of the solar flares duration time. The crosses correspond to the calculations produced with the data subset consisting of the flares with $E_p > 14\ c/\text{s}$.

as crosses. All exponents μ_p practically turned out to be equal to zero for this subset as it is expected for the Poissonian distribution (which has no clusterization).

4. Conclusions

In this Letter we compare results of our laboratory thermal convection experiment (see for detail description of the experiment [1] and references therein) with results of the observations produced by the RHESSI between 12 February 2002 and 15 April 2003. The main object of our consideration are duration times of the observed metastable states. In the case of the laboratory experiment the metastable states are defined as states with a certain direction of the thermal wind rotation and for the solar corona the metastable states are identified with the flares. We show that the probability density of the duration times in both these cases exhibit the same distinctive power law with the exponent -1 ± 0.1 and the exponential tails (cf. [7,10]). We also compare clusterization in the data sets. For this purpose we use a multiscaling analysis which resembles the analysis used for the critical phenomena [11]. We show that the multiscaling exponents characterizing clusterization also take very close values for the two types of the metastable states (thermal wind reversals and flares). Thus, both probability distribution and clusterization of the duration times exhibit quantitatively similar properties for the laboratory and for the solar metastable states.

On the basis of these observations one can speculate that the physical origin of both these phenomena has the same nature (we believe that this is SOC [1]; [7]). Relation between these two phenomena may be even more direct (not only through the SOC), because of possible existence of the thermal (convection) wind reversals in the solar corona.

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