CHARACTERIZATION OF LOCAL SELF-SIMILARITY AND CRITICALITY IN THE SOLAR ACTIVE REGIONS

R. R. Rosa 1, H.O. Vats 2,3, F. M. Ramos 1, A. Zanandrea 1, C. Rodrigues Neto 1, F. C. R. Fernandes 3, M. J. A. Bolzan 1, E. L. Rempel 1, R. C. Brito 1, N. L. Vijaykumar 1, and H. S. Sawant 3

1 Lab for Computing and Applied Mathematics (LAC), National Institute for Space Research-INPE, C.P. 515, 12201-970, São José dos Campos, Brazil
2 Physical Research Laboratory, Ahmedabad, 380009, India
3 Astrophysics Division (DAS) - INPE, Cx. P. 515, 12201-970, São José dos Campos, Brazil

ABSTRACT

From solar radio burst data we computed wavelet transforms and frequency distribution for investigation of self-similar temporal variability and power-laws, as the fundamental conditions for characterization of dynamical criticality (self or forced) in the solar active regions. The main result indicates that, as for the global activity, the local coronal magnetic field, in millisecond time scales, can be in a critical state where the dynamics of solar active regions works as avalanches of many small intermittent particle acceleration events.

INTRODUCTION

The concept of self-organized criticality (SOC), was proposed by Bak et al. (1987) to explain the prevalence of power-law, or scale-invariant, correlations extending over many decades in complex dynamical systems. They show that extended systems with many metastable states can naturally evolve into a critical state with no intrinsic length or time scale. The canonical example of such a system is a sandpile. In the critical state, the sandpile has a distribution of minimally stable regions of all sizes so that small perturbations give rise to avalanches of all sizes from the smallest possible avalanche (a single sand grain), up to the size of the system, so that there is no characteristic length scale. The spectral index of the resulting power-law avalanche size distribution is robust and suggests that the same mechanism works on all scales. The existence of a self-organized critical state requires a local instability which occurs whenever some local parameter exceeds a critical value, resulting in a transport process which can cause the value of the parameter at neighboring sites of the system to exceed the critical value. According to the SOC formalism (Bak, 1997) the organization into the critical point occurs without any external organizing force. However, as shown by Chang et al. (1992), using the concepts of path integrals and renormalization group, forced (not only self) nonlinear stochastic systems near criticality can also exhibit scaling free power-laws. Thus, a complementary analysis, such as self-similarity characterization plus geometric investigation of relevant scaling directions in the phase space, is also necessary to determine if the criticality is related only to self-organization mechanism.

Recently, Lu and Hamilton (Lu and Hamilton, 1991; Lu et al., 1993), have constructed the so-called LH model of solar flares based on the SOC phenomenon. In this model, the local magnetic instability can be thought of as the toppling grain of sand that triggers an avalanche of further magnetic instabilities in the solar corona. This avalanche is the solar flare which is observed to have a large dynamical range in both energy and lifetime. Lu et al. (1993) calculated the energy distribution of the flares, and also their distributions for peak flux and duration with a given energy. The power law index, \( \alpha \), for the total energy distribution was found to be \( \approx -1.5 \) which compares well with the values calculated from solar X-ray data (Crosby et al., 1993). Actually, the so-called statistical flare model (e.g., LH model) and/or solar flare frequency distribution spectra have been investigated by many authors working on observed and/or...
simulated solar activity data (e.g., Akabane, 1956; Crosby et al., 1993; Isliker, 1996; Bromund et al., 1995; Lawrence et al., 1995; Karlicky et al., 1996; Mercier and Trottet, 1997; Kucera et al., 1997; MacKinnon and Macpherson, 1997; Georgoulis and Vlahos, 1998; Dmitruk and Gomez, 1997; Schwarz et al., 1998; Vassiliadis et al., 1998; Aschwanden et al., 1998a,b; Anastasiadis, 1999; Wheatland, 2000). Basically, all results from observations and simulations produce power-law distributions of events compatible with the Gutenberg-Richter law (intensity distribution with a constant negative slope).

To investigate further the implications of dynamical criticality for the spatio-temporal statistical flare model, we here extend the avalanche scenario in an attempt to present a preliminary systematic analysis of the millisecond solar radio bursts. In the present approach the energy distributions of intermittent spikes during a solar burst (metric noise storm and decimetric pulsations) are taken in the same way as flares and nanoflares are taken for the global solar activity.

In the following section, we describe the data and analysis used in this study. In section 3, we present the results and interpretation. The final section contains a discussion on the characterization of criticality and its physical interpretation in the context of nonlinear plasma processes occurring in the solar corona.

DATA DESCRIPTION AND ANALYSIS

The data we use are representative of two particular solar radio bursts: (a) a metric noise storm, flare related, in the frequency of 164 MHz and (b) a decimetric pulsation, flare related, in the frequency of 1.6 GHz. The noise storm was observed by the Nancay Radioheliograph at 164 MHz with time resolution of 50 ms. This time series has 7197 points and was recorded from 14:19:14.49 UT in 4/21/92. The intensity is given in solar flux units (SFU). The instrument and data are described by the Radioheliograph Group (1989, 1993) and Mercier and Trottet (1997), respectively. The decimetric pulsation was observed by the Brazilian Solar Spectroscope at National Institute for Space Research (INPE) at 1.6 GHz with time resolution of 100 ms. This time series has 3000 points and was recorded from 16:24:24.27 UT in 4/29/98. The intensity is given in arbitrary units. The instrument is described by Sawant and Rosa (1990) and Sawant et al. (1993).

As a first kind of analysis we calculated the spike distributions for both events. In Figure 1 are shown the time series and their respective log-log plot of intensity distribution: (a) a metric noise storm and (b) a decimetric pulsation. This analysis is able to compute the respective power-laws and characterizes the presence or not of scale-free phenomena. In other words, it verifies if the fragmentation under consideration has no characteristic spatial scale above an elementary scale of the smallest critical structure up to the system size, the size of the radio source.

The second complementary analysis is based on wavelet transform technique (Fargé, 1992). The wavelet transform of \( x(t) \) is the decomposition into a set of functions \( w_{a,b}(t) = a^{-1/2}w[a^{-1}(t - b)] \), all derived from the mother wavelet (MW) by translation \( b \) and scaling \( a \) (e.g., Torrence and Compo, 1998). Wavelet analysis is a powerful tool to investigate stochastic signals and short lived structures. The MW may be chosen to best reveal the structure of the signal under consideration. In order to do this, we choose two appropriate MWs: (i) the Morlet wavelet (Percival and Walden, 2000) and (ii) the so-called DB5 wavelet (Daubechies, 1992).

The time-average of the square modulus of the wavelet coefficients over the scalograms, normalized by the variance of the signal, is the so-called global wavelet spectrum (GWS) (Amaral et al., 1998). GWS can be considered as a measure which permits us to identify power laws in the wavelet power spectra (the power law index from scalograms are here denoted by \( \beta_u \)) as usually introduced by the wavelet transform modulus maxima technique (Arneodo et al., 1995). As shown by Rodrigues Neto et al. (1999), from the estimation of the global wavelet spectrum, it is possible to identify the presence of signal intrinsic self-similarity, characterized when the power-law is positive (the canonical example is the Random Koch index that is in the range 1.0 to 2.1 when calculated from global wavelet spectra). A positive value of \( \beta_u \) suggests that a signature of the spectral similarity (the so-called Gutenberg-Richter law), characterized by means of the frequency distribution, is also present in the time domain indicating a fractal fragmentation of the released energy.

The wavelet spectra (DB5 and Morlet) of the millisecond time resolution events (metric and decimetric) were obtained with dyadic scales from 1 to 9. The Morlet spectra are shown on the left side of Figure 2.
The corresponding global wavelet spectrum (GWS) are shown on the right side of Figure 2. The results are introduced and interpreted in the next section.

RESULTS AND INTERPRETATION

In Figures 1c and 1d are shown the log-log plot of intensity distribution for both time series. The straight line through the boxes represents the least-squares fitted power law function. The slope exponents for the intensities distributions are, respectively, \( \alpha_{164} = -1.65 \) and \( \alpha_{1.6} = -2.10 \). The positive slope before the turn-over observed in the lower end of the 1.6 GHz intensity frequency distribution (Figure 1d) is due to approximately 10% of small spikes whose level is in the range of intensity between 0 and 50, which is the range of noise, in arbitrary units, recorded by the instrument (Sawant et al., 1993). These power-laws (fig. 1c and 1d) show that the high spikes amplitudes (\( \gg \sigma \)) are less frequent than that of small amplitudes (\( \approx 3\sigma \)), where \( \sigma \) is the standard deviation for a set of spikes taken into a sub-range of 25 seconds. In the time domain, for the 164 MHz noise storm, an average of 3.5 spikes whose intensity is \( \approx 3\sigma \) occur before a single spike whose intensity is \( \gg \sigma \). For the 1.6 GHz decimetric pulsation this rate is in the range of 5 to 15 spikes. These power-laws and avalanche behavior confirm the qualitative flare Gutenberg-Richter law reported in several papers (see Wheatland (2000) and references therein) and is quite consistent with predictions of the cellular automata LH model for the occurrence of flares during the solar activity.

![Fig. 1. Solar bursts and their respective histograms with the best fit for the main part of each distribution. (a) The noise storm observed by the Nancay Radioheliograph at 164 MHz with time resolution of 50 ms recorded from 14:19:14.49,UT in 4/21/92. (b) The decimetric pulsation observed by the Brazilian Decimetric Spectroscope at 1.6 GHz with time resolution of 100 ms recorded from 16:24:24.27 UT in 4/29/98. (c) Distribution of spikes of noise storm shown in Figure a, yielding a slope of -1.65. (d) Distribution of spikes of decimetric pulsation shown in Figure b, yielding a slope of -2.10.](image_url)

The combination of dynamical minimal stability and spatial scaling leads to a power law (self-similar spectra) for temporal fluctuations, and at the critical point there is a distribution of spikes of all observable intensities. However, how do we characterize the presence of self-similarity in the time domain? In Figure 2 are shown the scalograms for the time series of Figure 1 and their respective global wavelet spectra. In both cases the temporal self-similarity is well characterized by the positive GWS slopes: \( \beta_{w,164} = +0.56 \) and \( \beta_{w,1.6} = +0.57 \). It means that there is a strong self-similarity in the temporal variability of radio storms and
pulsations, confirming the occurrence of small spikes before each single big spike, in different ranges, along the whole series. This result is strongly consistent with localized turbulence driven by intermittency. This result was reported by Rosa et al. (1997) based on the analysis of spatio-temporal soft X-ray coronal active regions by using the asymmetric amplitude fragmentation technique (Rosa et al., 1999). Indeed, turbulence is a phenomenon where self-similarity is believed to occur both in time and space (Bak et al., 1987).

Fig. 2. The scalograms and global wavelet spectra for the solar bursts of Figure 1. (a) Morlet scalogram for 164 MHz time series and its respective (c) GWS yielding a slope of +0.56. (b) Morlet scalogram for 1.6 GHz time series and its respective (d) GWS yielding a slope of +0.57.

CONCLUDING REMARKS

The results of our analyses have shown that the Gutenberg-Richter law is also present in the millisecond scale of solar burst variability. According to these preliminary results, the measured distributions of metric and decimetric spikes during a solar burst are also governed, as flares and nanoflares during the solar cycle, by a stochastic avalanche mechanism. However, how do frequency distributions of flares relate to those of elementary time structures during individual active events? Although the physical emission mechanisms of flares (e.g., radio and X-ray signatures) of metric noise storms and of decimetric pulsations are different, the solar active regions can be interpreted as examples of a class of driven dissipative systems whose long-term statistical behavior is characterized by a power-law distribution of energy avalanches, as given by dynamical critical phenomena, where scale-free intermittency plays a fundamental role.

Recently, Georgoulis and Vlahos (1998) introduced a more consistent SOC model where the power-law
indices obtained from flaring and nanoflaring activity are by no means unique: an inhomogeneous external driver produces occurrence frequency variability. Taking into account this modified SOC model, our results agree with the possible variability of the occurrence frequency of radio bursts and confirm the preliminary investigation of decimetric millisecond spikes performed by Aschwanden et al. (1998a).

However, the nature of such observed criticality is still under investigation. In fact, power-law and self-similarity are not sufficient conditions to characterize the self aspect of SOC, once the stochastic behavior of nonlinear dynamical system can be also generated by near forced critical conditions whose nature is compatible with nonlinear instabilities in plasma processes (e.g. Chang, 1999). Therefore, we are currently pursuing three complementary analyses of a larger sample of radio bursts: (1) investigation on correlations between radio fragmentation and turbulent instabilities observed in X-ray (Rosa et al., 2001a), (2) a geometric analysis of relevant scaling directions in the N-parameter affine space where the criticality manifold of millisecond solar bursts can be investigated (Rosa et al., 2001b) and (3) a more detailed statistical analysis on the spikes' waiting-time distribution.

Such analyses and results will be useful to better understand the foundation of dynamic criticality (self and/or forced), a concept still under investigation in the context of the phenomenological framework of nonstationary avalanche models for both local and global solar activity.

ACKNOWLEDGMENTS

We are indebted to G. Consolini for useful discussions and also grateful to the referees for valuable suggestions. The authors are grateful to the agencies FAPESP (Proc. 97/13374-1, 98/03104-0, 98/03105-6, 99/10529-0 and 00/04215-1), FINEP (Proc. PAD 370/96) and CNPq (Proc. 301049/98-0). The 164MHz data was provided by Dr. Jean Pierre Raulin.

REFERENCES


