2002ESASP.506..737R

RADIO SIGNATURE OF MULTI-SCALING FLARE LOOP INTERACTIONS

Reinaldo R. Rosa[1], **Fernando M. Ramos**[1], **Hanumant S. Sawant**[1], **Francisco C. R. Fernandes**[1],
Nandamudi L. Vijaykumar[1], **Ademilson Zanandrea**[2], **and Marian Karlický**[3]

[1]National Institute for Space Research (INPE), 12245-970 S.J.Campos-SP, Brazil
[2]Division of Electronic Engeneering, Technological Institute of Aeronautis (ITA), Sao Jose dos Campos, SP, Brazil
[3]Astronomical Institute of the Academy of Sciences of the Czech Republic, CZ-25165 Ondřejov, Czech Republic

ABSTRACT

The solar radio emission at 3GHz observed during the June 6, 2000 flare, at times when the EIT/SOHO and SXT/*Yohkoh* images indicate the flare loop interactions, has been analyzed for its complex temporal variability. Using the Fourier Power Spectrum (FPS) and the Global Wavelet Spectrum (GWS) techniques the power spectra of the 3GHz signal, observed with time resolution of 0.6 s, have been determined: a $1/f^{1.66\pm0.16}$ power law. The presence of a characteristic power-law implies that the fluctuations are stochastically correlated without a dominant characteristic spatio-temporal scale and contain some self-similarity in time.

Key words: Sun:flares - Sun:radio radiation - Method:spectral analysis.

1. INTRODUCTION

There are observations indicating the importance of mutual loop interactions for the energy release processes in the solar atmosphere and solar flares (Shimizu et al. 1992, Smartt et al. 1993, Šimberová et al. 1993, Wang et al. 2002, Fárník and Karlický 2002). On the other hand, theoretical models of the solar flares consider the interaction of the current-carrying loops as the primary flare process (for review see Sakai & de Jager, 1996). According to Finn and Kaw (1977) and Pritchett and Wu (1979) the MHD coalescence instability is a process that involves bulk current redistribution typically in Alfvén time scale. This is a typical nonlinear process of reconnection, probably triggered as a secondary process by the primary instability (Bhattacharjee et al, 1983). Based on this formalism, Tajima et al. (1987) presented the model with the nonlinear coalescence instability of interacting current loops. They recognized the quasi-periodic regime of these processes and they derived their characteristic period T_{OS} of nonlinear oscillations:

$$T_{OS} = 2\pi(-2E)^{-3/2}t_A^{-2}, \tag{1}$$

where E is the initial "energy" of the system, $t_A = \lambda/v_A$ with λ being the magnetic field scale length and v_A is the Alfvén speed. The period T_{OS} becomes longer when E tends to zero and tends to a minimum value T_{min} when E tends to the minimum Sagdeev potential $-v_A^2/2\lambda^2\gamma$:

$$T_{min} = 2\pi\gamma^{3/2}t_A, \tag{2}$$

where γ is the the ratio between the kinetic and magnetic energy densities.

Tajima et al. (1987) used this model for the interpretation of the quasi-periodic variations of the radio emission in the microwave range. They assumed that the quasi-periodic electric field, generated during the two-loop coalescence processes, accelerate electrons and these electrons produce the observed radio emission. However, usually not only two current loops, but multiple current structures can also participate in the current loop coalescence process. All the filamentary currents can interact in the same way as described in the Tajima et al. (1987) model, but in a multi-scale process. In the solar atmospheric plasma such mechanism can be a scaling free process, as in the case of flares and nanoflares occurrence distribution (e.g. Wheatland (2000) and references therein) or millisecond time scales in a single flare observed in the metric and decimetric ranges (Rosa et al., 2002a), indicating that the radio observations can demonstrate a more general picture of the interacting loops.

In this paper, the high-frequency radio emission at instants where brightenings between the parallel loops, observed by EIT/SOHO and SXT/*Yohkoh* indicating their interaction, is shown, and the spectral

Proc. 10th. European Solar Physics Meeting, 'Solar Variability: From Core to Outer Frontiers', Prague, Czech Republic, 9-14 September 2002 (ESA SP-506, December 2002)

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analysis (Fourier and Wavelets) of the 3 GHz radio flux variations is performed revealing some statistical characteristics of the fluctuations probably correlated to the loop nonlinear oscillations. Thus, the results are interpreted in the context of multiple current loop coalescence process.

2. DATA

The June 6, 2000 flare, classified as X2.3, was observed during 15:00-17:00 UT in the active region NOAA AR 9026. A full-halo coronal mass ejection and the type II radio burst were reported in association with this flare (Solar Flare NOAA Report). During the flare, two impulsive phases at 15:14-15:40 UT and 16:34-16:40 UT were observed by the Ondřejov radiospectrograph (Jiřička et al. 1993). During the first impulsive phase the broadband pulsations and continuum were recorded, whereas during the second impulsive phase the pulses (bandwidth ~ 800 MHz, duration ~ 5s) consisting of many narrowband spikes were observed (Rosa et al., 2002b). The pulses seen in the spectrum correspond to the quasi-periodic peaks observed in the 3 GHz radio flux record. The second phase of the flare was also observed by the the EIT/SOHO and SXT/*Yohkoh* instruments. The EIT 195 Å image at 16:36:11 UT and that of SXT/*Yohkoh* observed at 16:36:41 UT (Figure 1) show an arcade of parallel flare loops with brightenings between them, indicating loop-loop interactions. According to the model of Tajima et al. (1987) we interpret the 3 GHz radio flux variations as radio manifestations of the loop interactions. To understand these interacting processes, we analyze the time variations of the 3 GHz radio flux by the Fourier and wavelet analysis methods. These analyses are performed in the full time interval of 16:34:00-16:40:00 UT (Figure 2a) with time resolution of 0.6s (a time series composed by 600 points).

3. DATA ANALYSIS

3.1. Wavelet Decomposition

Our spectral analysis uses both the Fast Fourier Transform (FFT) and wavelet transform techniques (e.g. Farge, 1992; Torrence and Compo, 2002). The wavelet transform of a quantitity $x(t)$ is its deconvolution into a set of functions $w_{a,b}$ where $w_{a,b}(t) = a^{-1/2}w[a^{-1}(t-b)]$, all derived from the *mother wavelet* (MW) by translation b and scaling a (e.g. Torrence and Compo, 1998). The wavelet analysis is a powerful tool to investigate stochastic signals and short lived structures (Percival and Walden, 2000). The MW may be chosen to best reveal the structure of the signal under consideration and for very short time scale variability under nonlinear modulation we choose the Morlet wavelet (Morlet, 1983). Figure 2b shows one level of the multilevel wavelet signal decomposition. A precise methodology for wavelet multiresolution signal decomposition is given by Mallat (1989).

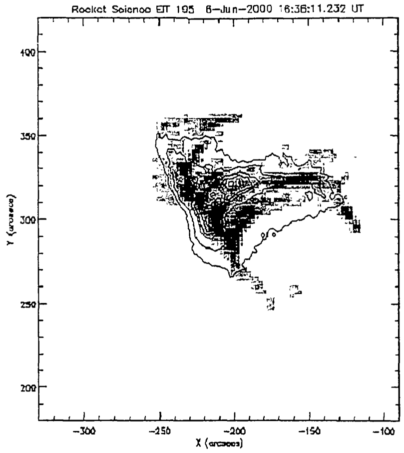

Figure 1. The Yohkoh*/SXT image (16:36:41 UT, contours) superimposed on the EIT/SOHO 195 Å image at 16:36:11 UT.*

Wavelet decomposition was made for 6 levels. This decomposition structure respectively corresponds to $(32 - 64 \times 0.6)$ scale limits of the band-pass decomposition filter. It can be seen that larger structures or low-frequency package of the original signal appear in this decomposition. This analysis permits us to infer that our range of temporal variability goes from 0.01s (given by the best time resolution of the instrument, not analyzed in this paper) up to 45s (given by the lowest variability component of our decomposition). This time scale corresponds to a frequency modulation of $\approx 0.01Hz$ as shown in Figure 2b.

3.2. The Global Wavelet Spectra (GWS) and the Fourier Power Spectrum (FPS)

The wavelet power spectrum (spectrograms) were obtained following a dyadic scales, using one scale at each of octave from 1 to 9. The time-scale of the real part of wavelet coeficients of the respective time series are shown in Fig 2c. The time-average of the square modulus of the wavelet coefficients over the scalograms is the so-called ***global wavelet spectrum*** (GWS) (Mallat,89; Torrence and Compo, 2002). The GWS permits us to identify the possible presence of the power laws in the wavelet power spectra. The power law index from the scalogram is denoted by β_w, usually determined by the wavelet transform modulus maxima technique (Amaral et al. 1998).

It is worth noticing that in the wavelet decomposi-

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tion all decomposed signals have the same wavelet spectral index (β_w), so that they are self-similar in a log-log slope and from them it is possible to construct a global spectrum of the signal.

Essentially, the absolute values for spectral indices obtained from a FPS and GWS should be the same. This expectation occurs because the slopes in a log-log plot obtained as $P(f) \times f$ and as $P(a) \times a$, where P is the power density of frequency (f) or scale (a), are analytically equivalent (Torrence and Compo, 1998). However, as shown by Torrence and Compo (2002), at small wavelet scales (high frequency), the wavelet is very broad in frequency, therefore any peaks in the spectrum get smoothed out. At large wavelet scales, the wavelet is narrower in frequency, therefore the peaks are sharper and have a larger amplitude. In mathematical terms, the global wavelet spectrum is an "efficient" estimator of the "true" power spectrum, but it is also "biased". The bias means that there may be a large difference between the global wavelet spectrum and the "true" Fourier spectrum. Thus, the best way to make a power spectra analysis of real data when the signal has a large range of frequency (or scales) is to combine both techniques, FPS and GWS as the following methodology:

- shorter scales should be determined by FPS decomposition and its spectral index, β_F, is a more "efficient" estimator of the "true" (α) power spectrum;
- larger scales should be determined by GWS decomposition and its spectral index, β_W, is a more "efficient" estimator of the "true" (α) power spectrum;
- the absolute value of the "true" spectral index, β, for all frequency scales, can be assumed as the average beetween the absolute values of β_F and β_W. In a *strong condition* the time resolution for the whole signal must be the same.

As shown by Rodrigues Neto et al. (1999), from the estimation of the *global wavelet spectrum*, it is also possible to identify the presence of intrinsic self-similarity in a signal. The self-similarity is characterized when the power-law, β_W is positive. The canonical example is the Random Koch index that is $\sim 1.55 \pm 0.55$ when calculated from several global wavelet spectra. For a pure white noise (generated from a stochastic process without any memory) the value of β_w is zero. Moreover, a nonstationary stochastic process characterized by a power spectrum with the functional form $S(f) \sim 1/f^{\alpha}$ is short-range correlated (not Markovian) for $\alpha = 2$ and long-range correlated for $\alpha \approx 1$.

3.3. Results

The wavelet spectra of the 3 GHz radiation, observed with time resolution of 0.6 s, was obtained with dyadic scales from 1 to 10. Figures 2c and 2d show the respective scalograms and corresponding global wavelet spectra (for the time series showed in Figure 2a, and its respective spectral index β_F is reported in Figure 2e. Considering the absolute values of $| \beta_F | = 1.77$ and $| \beta_W | = 1.54$ for the analyzed time series, its "true" spectral index must be reported as $| \alpha | = 1.66 \pm 0.16$.

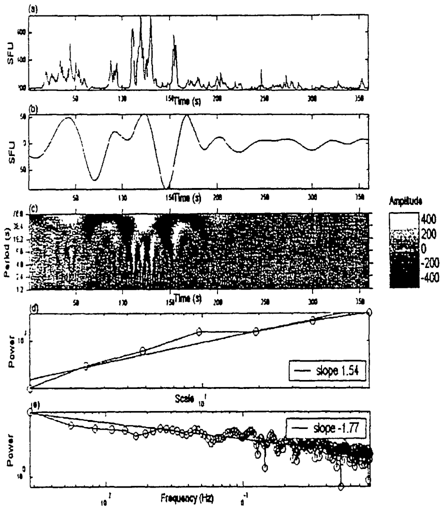

Figure 2. (a) The full 3.0 GHz time series (16:34:00-16:40:00 UT) and its (b) 6th wavelet decomposition,(c) Histogram and (d) Fourier Power Spectrum

4. CONCLUDING REMARKS

The signatures of the multi-scaling flare loop interactions are reported here for the first time. Our result ($1/f^{1.66 \pm 0.16}$ power-law) is related to the stochastic behavior of a nonlinear dynamical system near forced and/or self-organized criticality (FSOC). Physically, it is scaling free and behaves as a self-correlated intermittent stochastic process. This suggestes that there is a bunch of many parallel interacting current loops and each specific loop may again consist of a bunch of the filamentary sub-currents. In such a system there is a wide range of possible spatio-temporal scales. All the filamentary currents can interact as a multi-scale process. The loop interaction scales can be ranging from very small to very large spatio-temporal scales. In the pure time domain one can say this range goes from, at least, 0.01s up (the best time resolution for 3GHz data) to $\sim$ 1 minute time scales (computed by means of Wavelet decomposition). In such a scale free and spatio-temporal correlated scenario a multiscale intermittent turbulence of overlapping plasma resonance can lead to the

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onset and evolution of MHD coalescence instability. This stochastic behavior of coherent plasma structures can undergo complex changes as the nonlinear dynamic system evolves, similar to those commonly observed in dynamical phase transitions.

In particular, the 3GHz radio observations combined with EIT/SOHO 195 Å and SXT/*Yohkoh* images have demonstrated a more general picture of the interacting loops, as a cluster of spatio-temporal scales. In some rare cases it may happen that there exists a dominant scale to generate a specific time period of the nonlinear oscillations. The presence or absence of specific periods is also a function of the spatio-temporal resolution of the observations, indicating a self-similar turbulent fragmentation of the released energy. The nature of intermittency and turbulence of the signal will be investigated by means of the gradient pattern analysis (Assireu et al. 2002).

In order to characterize the presence of a robust stochastic self-similarity due to scaling free dynamical topological phase transitions, a complementary computation of β_F and β_W for 3GHz radio observations with time resolution of 0.01 s is also in progress (Rosa et al., 2002b) and will be communicated later.

ACKNOWLEDGMENTS

RRR and AZ are grateful to the Brazilian funding agency FAPESP under grants 97/13374-1 and 00/10043-9. M.K. thanks FAPESP authorities for supporting his visit to INPE. This work was also supported by the grants A3003202 and S1003006, AS-CR.

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