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Nonlinear analysis of decimetric solar bursts

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Abstract. The solar radio emissions in the decimetric frequency range (above 1 GHz) are very rich in temporal and spectral fine structures due to nonlinear processes occurring in the magnetic structures on the corresponding active regions. In this paper we characterize the singularity spectrum, $f(\alpha)$, for solar bursts observed at 1.6, 2.0 and 3 GHz. We interpret our findings as evidence of inhomogeneous plasma turbulence driving the underlying plasma emission process and discuss the nonlinear multifractal approach into the context of geoeffective solar active regions.

Keywords. turbulence, Sun: radio radiation, solar-terrestrial relations; methods: data analysis

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1. Introduction

Solar energetic events, as solar flares, produce typical radio emission patterns throughout the whole radio emission spectrum range. In particular, several physical aspects of the active region are related to the high resolution and high sensitivity data observed in the lowest microwave range (1–3 GHz), usually reported as the decimetric range (Aschawanden 2005). Usually the solar flare process is related to a magneto-hydrodynamic (MHD) instability taking place in strongly anisotropic turbulent plasma (Kuperus, 1976). The importance of this MHD scenario has been investigated, for example, from nonlinear analysis of decimetric bursts at 3 GHz observed during the June 6, 2000 flare (Rosa *et al.* 2008). It was found that the 3 GHz radio burst power spectrum exhibits a power-law which is an evidence of stochastic intermittency due to a self-affine dynamics as found in the MHD turbulence theory. Intermittent energetic process implies that the fluctuations are correlated without a dominant characteristic time scale, as predicted in the models for multi-loop interactions (Tajima 1987). However, in order to characterize more precisely the nature of such inhomogeneous self-affine turbulent process, a complementary analysis, based on the so-called singularity spectrum technique, is required.

As known from the turbulence theory, the intermittency leads to deviation from usual Kolmogorov energy structure functions and its main signature are the singularity spectra exponents, $f(\alpha)$, which represent a power-law scaling-free dependence (Frisch 1995). For inhomogeneous plasma turbulence, the so-called multi-fractal *p-model* describes how the energy can be distributed among scales following a multiplicative rescaling structure (Halsey *et al.* 1986). In this paper, taking into account the *p-model* singularity spectra, we obtain the $f(\alpha)$ for typical decimetric bursts, improving our search for a robust technique by which inhomogeneous plasma turbulence process might be identified.

2. Data Analysis, Interpretation and Discussion

Fig. 1 shows the intermittent time series observed at 1.6 GHz (a), 2 GHz (b) and 3 GHz (c). The decimetric bursts at 1.6 (Fig. 1a) and 2 GHz (Fig. 1b) were observed by using the Brazilian Solar Spectroscope (BSS) with time and frequency resolutions of 100ms and 10 MHz, respectively (Madsen *et al.* 2004). Figure 1c shows the 3 GHz burst observed employing the Ondrejov radiospectrograph with time resolution of 0.01s (Jiricka *et al.*, 1993). These three decimetric bursts were related to geoeffective energetic solar events as flares and Coronal Mass Ejections.

Here we have considered, in order to obtain the singularity spectrum $f(\alpha)$ from the SFU-component time series, the Wavelet Transform Modulus Maxima (WTMM) (Mallat 1989). The basic idea behind the WTMM method is to describe a nonlinear partition function over only the modulus maxima of the wavelet transform of a signal SFU(t). Recently, the robustness of this methodology has been tested for intermittent geomagnetic fluctuations using, as a reference nonlinear pattern, the so-called *p-model* (Halsey *et al.* 1986). The *p-model* is a canonical mathematical system that describes nonhomogeneous energy cascade processes in turbulent-like flows (e.g., Rodrigues Neto *et al.* 2001). In this process the flux density is transferred to the two smallest eddies with the same length but different flux probabilities p_1 and p_2 ($p_1 + p_2 = 1$). The process is repeated several times with p_1 and p_2 randomly distributed, being the asymmetric breakdown in the fragmentation process driven by the parameter $p = p_1 = 1 - p_2$. The common value of $p_1 = p_2 = 0.5$ corresponds to the homogeneous energy transfer rate with no intermittency effects. The values of $p > 0.5$ correspond to an intermittent nonlinear dynamics found in nonhomogeneous turbulence and chaotic advection. In the present work, we use a maximum likelihood algorithm to fit the *p-model* in each characteristic solar burst scale. Hence we have performed the theoretical multiplicative cascade *p-model* as a canonical reference in our analysis.

Choosing typical parameters values for the *p-model* (Bolzan *et al.* 2009) we use an algorithm to fit the experimental and theoretical data. The results are shown in Fig. 2 from where the SFU complex pattern variability can be interpreted as the result of a possibly multifractal process related to the presence of a nonhomogeneous asymmetric energy cascade during the energy release process in the respective active regions. Characteristic values of the α for each $f(\alpha)_{max}$ show that the relation between the radio frequency and the multifractal spectrum characterized by means of α for each $f(\alpha)_{max}$ is nonlinear. This result makes evident the importance of studying in detail the presence of intermittent nonlinear phenomena driving the solar decimetric fluctuations during flares.

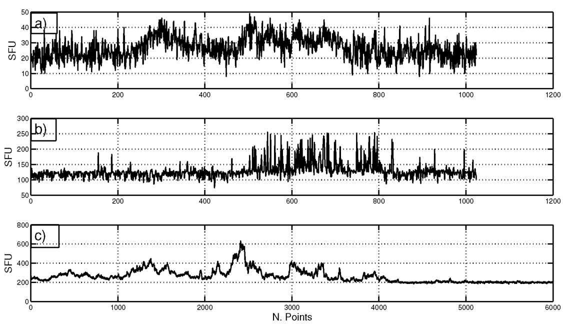

Figure 1. SFU times series for decimetric solar bursts observed at 1.6 GHz (a), 2 GHz (b) and 3 GHz (c).

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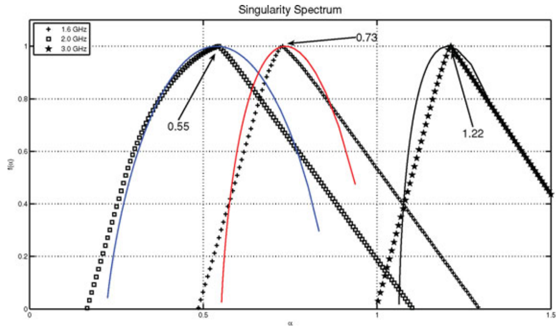

Figure 2. The singularity spectra for each SFU time series showed in Figure 1 and their corresponding *p-model* fitting. The values of the respective characteristic α for each $f(\alpha)_{max}$ are shown.

The inhomogeneous nature of the decimetric solar radio emission was successfully detected by using the WTMM. The decimetric SFU time series can be interpreted as being the response of an out-of-equilibrium process, possibly related to the particle acceleration from a transversal loop-loop interaction, where MHD oscillations can play an important role and a counterpart phenomena as turbulent interaction between electron beams and evaporation shocks can act as a secondary source. In order to check such hybrid mechanism composed by a inhomogeneous decimetric extended source higher spatial resolution data are required. Once the decimetric solar bursts analysed here are related to geoeffective events, the microphysics processes as particle acceleration and magnetic reconnection can be addressed in a more general framework involving the plasma solar-terrestrial environment.

3. Acknowledgements

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