SOLAR WIND COMPLEXITY

Iliopoulos A.C., PhD
Democritus University of Thrace
Department of Electrical and Computer Engineering
Xanthi, Greece

HELLENIC ASTRONOMICAL SOCIETY

The 11th Hellenic Astronomical Conference

8-12 September 2013, Athens

European Union
European Social Fund

OPERATIONAL PROGRAMME
EDUCATION AND LIFELONG LEARNING
investing in knowledge society
MINISTRY OF EDUCATION, LIFELONG LEARNING AND RELIGIOUS AFFAIRS
MANAGING AUTHORITY

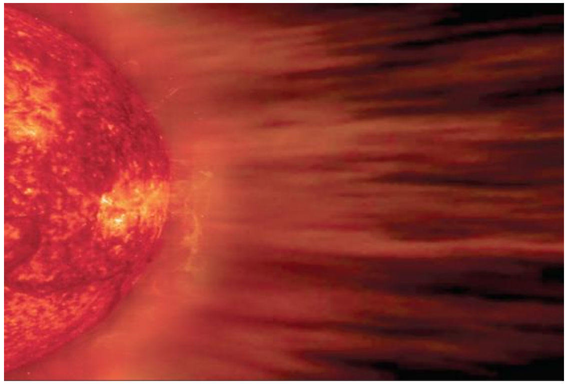
NSRF 2007-2013
programme for development
EUROPEAN SOCIAL FUND

Co- financed by Greece and the European Union

THE SOLAR WIND LABORATORY

Solar Wind includes ionized and magnetized gas, composed mainly by protons, electrons, alpha particles and heavier ions, continuously flowing away from the solar corona in all directions pervading the interplanetary space.

- Microstate
  - Ion composition and superthermal electrons
  - Coulomb collisions
  - Waves and Plasma microinstabilities
  - Diffusion and Wave-particle interaction



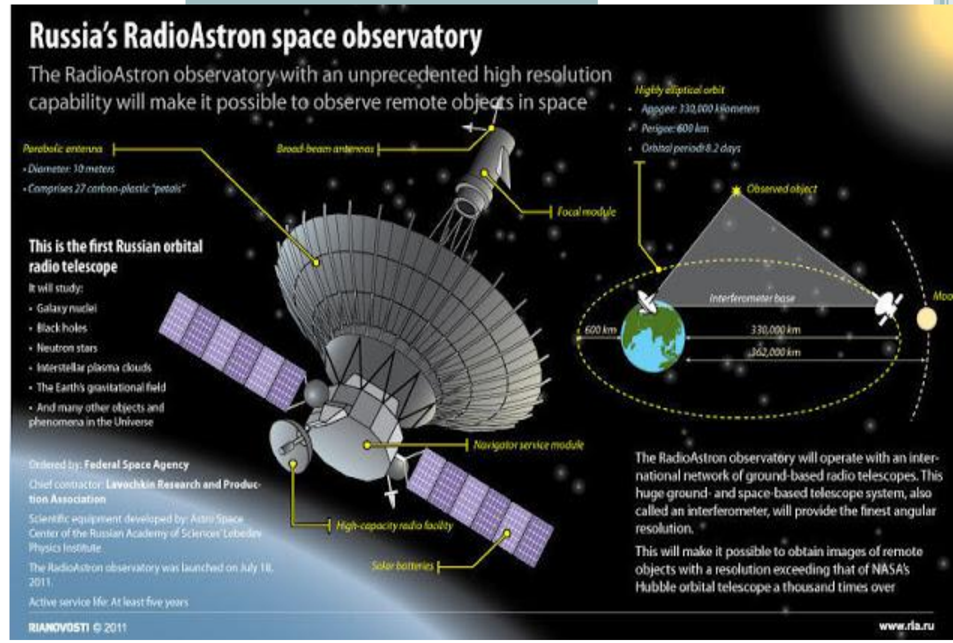
Solar Wind is a far from equilibrium, chaotic, self similar, multiscale, multifractal and intermittent MHD turbulent system.

- Characteristics
  - Nonequilibrium thermodynamics
  - Multicomponent and nuninform
  - Chaos
  - Power law scaling
  - MHD turbulence
  - Intermittency
  - Nonextensive statistics

e.g. March and Tu, (1997), Burlaga (1993), Carbone et al. (1996), Zelenyi and Milovanov (2004), Macek (2006)

Spectr-R Satellite – BMSW Instrument

The BMSW instrument is installed onboard the high-apogee Spectr-R satellite. This spacecraft was launched on July 18, 2011, into orbit with apogee of ~ 350 000 km, perigee of ~ 50000 km and orbital period of 8.5 days. The BMSW instrument has operated almost permanently since August 6, 2011.

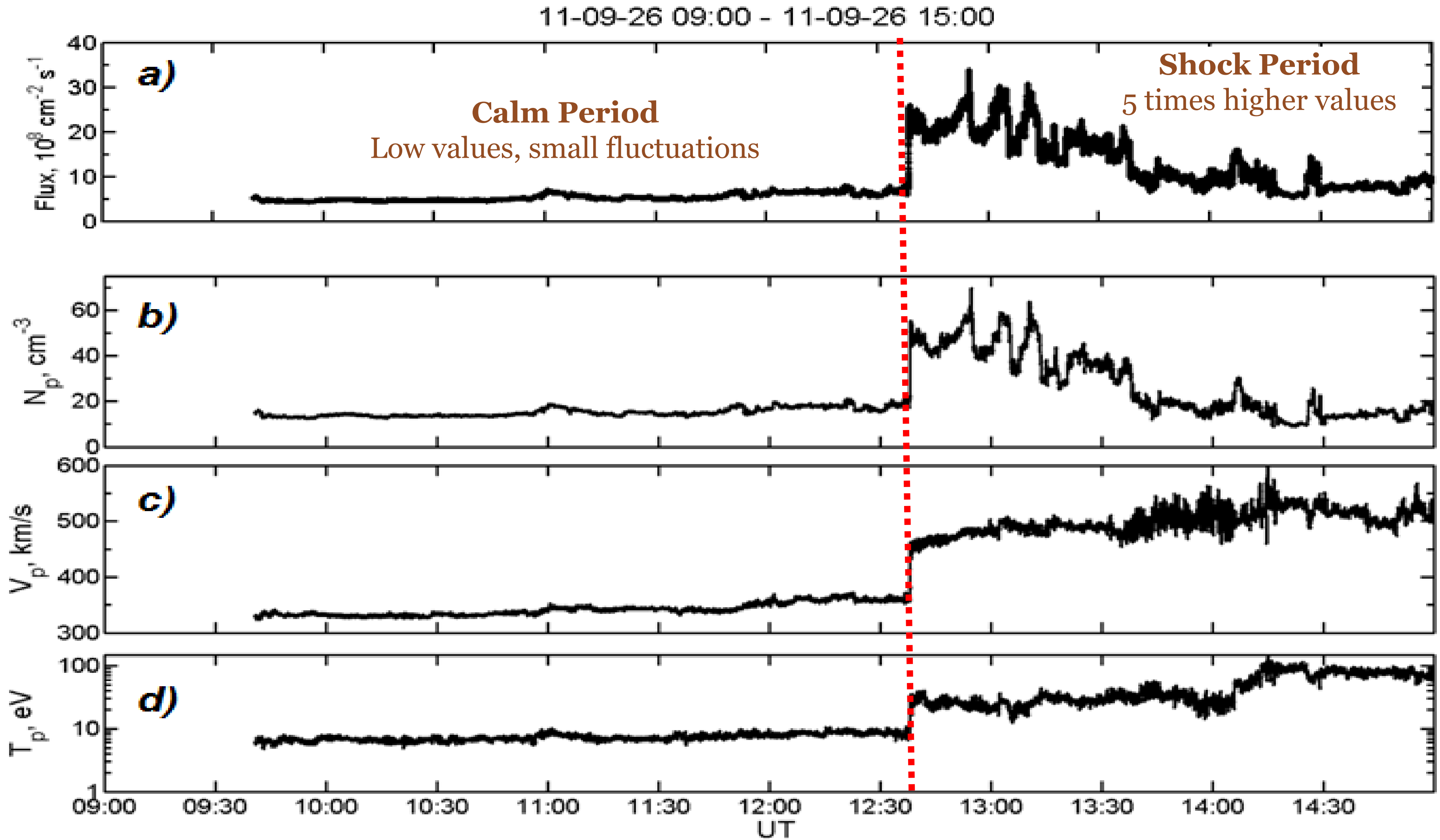


Zastenker *et al.* 2013 (IKI)

The BMSW instrument (Fast Monitor of the Solar Wind) was specially designed for measuring of solar wind plasma parameters with very high time resolution. The value of ion flux and it's direction are measured with resolution equal to 31 ms.

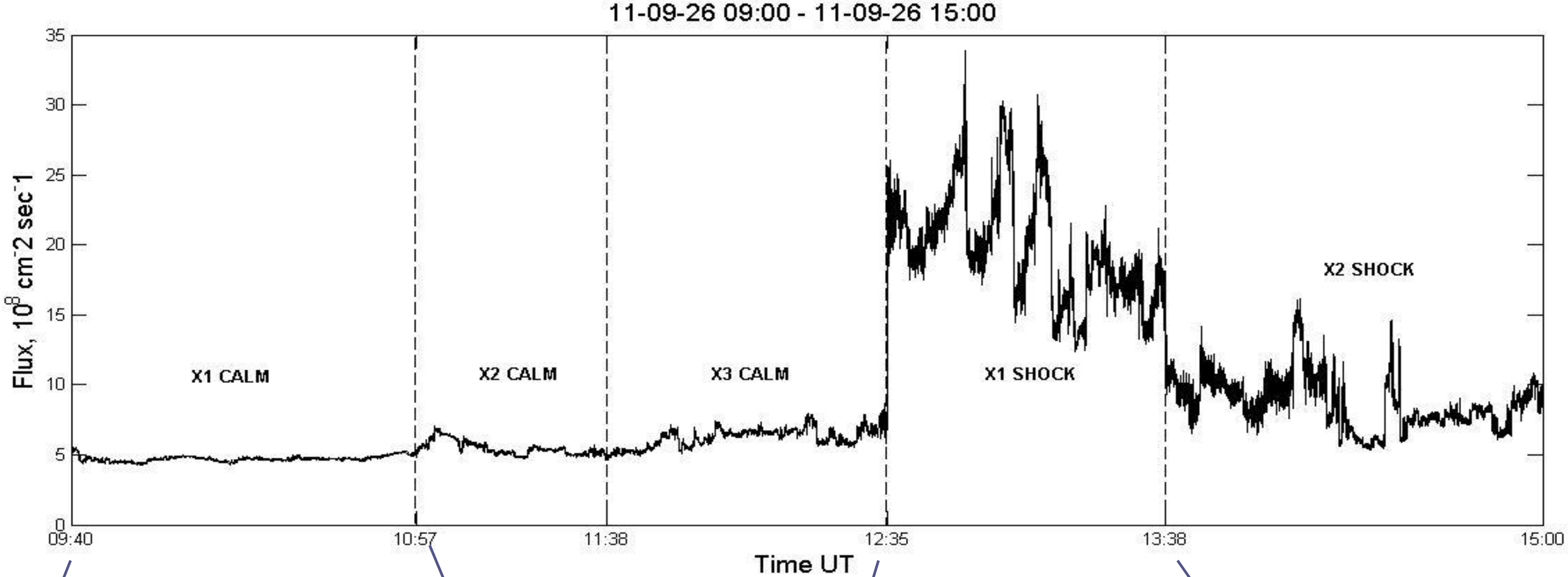
BMSW Data - Solar Wind Parameters

Ion Flux (a), density (b), velocity (c), temperature (d) on shock front 26.09.2011

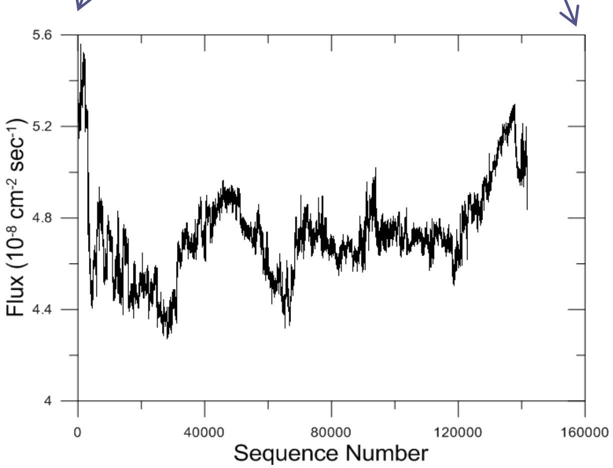


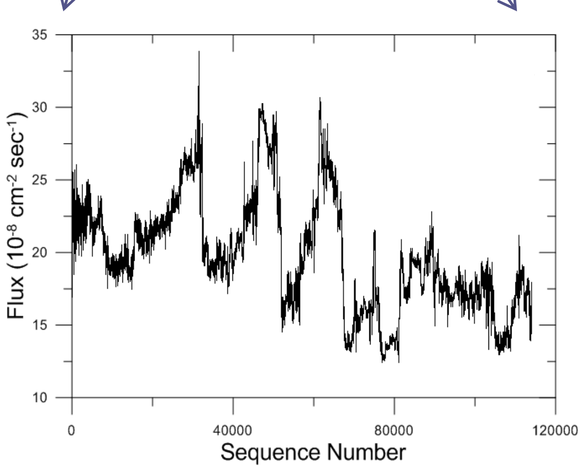
Time Series

Solar wind Ion Flux time series on shock front 26.09.2011 (12:35 UT)



N= 604.510 counts





CHAOTIC ALGORITHM

SLOPES OF THE CORRELATION INTEGRAL – *Estimating Degrees of Freedom (n)*

$$C_2(r) = \frac{2}{(N-W)(N-W-1)} \sum_{i=1}^{N} \sum_{j=1+W+1}^{N} \Theta(r - \|x(i) - x(j)\|)$$

Scaling

$$C(m,r) \sim r^{dm} \text{ για } r \to 0$$

$$d_m = \lim_{r \to 0} \frac{d[\ln C(m,r)]}{d[\ln(r)]}$$

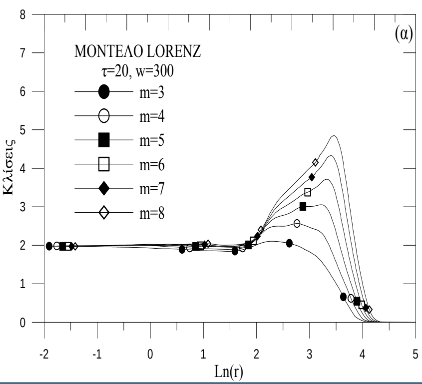
Heavyside Function $\Theta(x) = \begin{cases} 0, x \leq 0 \\ 1, x > 0 \end{cases}$

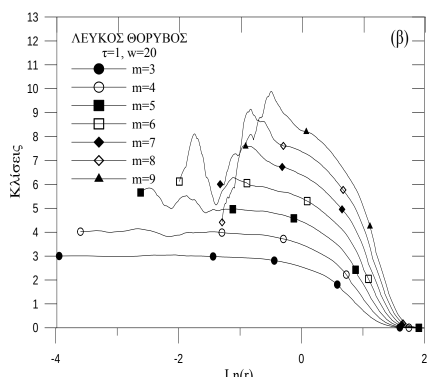
W Theiler parameter

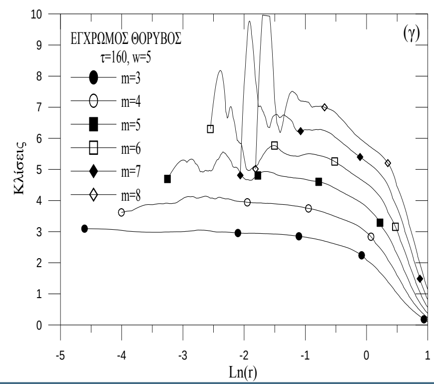
Saturation

$$D = \lim_{m \to \infty} d_m$$

$$n = 2D + 1$$







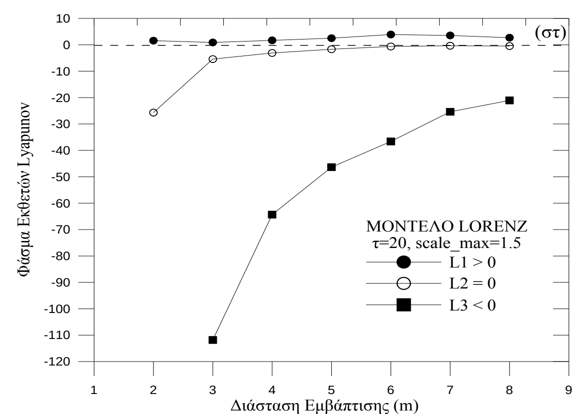
A surrogate is identical with the original time series in all phenomenological characteristics

- Autocorrelation
- Power Spectrum
- Probability Distribution
- Structure Function
- Flatness Coefficient F, Hurst Exponent H

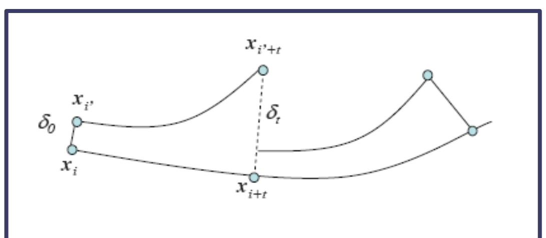
LYAPUNOV EXPONENTS

Sensitivity to Initial Conditions
(maximum Lyapunov exponent)
Lmax > 0 - Chaos

$$\lambda_1 = \frac{1}{Mt} \sum_{j}^{M} \ln \frac{\delta_{t,j}}{\delta_{0,j}}$$



Exponential Divergence of nearby trajectories in reconstructed phase space



TSALLIS *q*-TRIPLET – *Experimental Estimation*

Gaussian-BG equilibrium ($q_{stat}=q_{sen}=q_{rel}=1$) → Nonequilibrium ($q_{sen} < q_{stat} < q_{rel}$)

$$\frac{dy}{dx} = y^q \ , \ (y(0)=1, q \in \Re) \quad \rightarrow \quad (q_{stat},\ q_{sen},\ q_{rel})$$

characterize the attractor set of the dynamics in the phase space of the dynamics

(q_{stat})

$$PDF[\Delta Z] = A_q[1+(q-1)\beta_q(\Delta Z)^2]^{1/1-q}$$

$$\ln_q(P(z_i))\, vs\, z_i^2 \Leftrightarrow \ln_q(x) = (x^{1-q}-1)/(1-q)$$

$$G_q(\beta, z) = \frac{\sqrt{\beta}}{C_q} e_q^{-\beta z^2}$$

The stationary solutions P(x) describe the probabilistic character of the dynamics on the attractor set of the phase space

(q_{sen})

Mass Exponent

Renyi generalized dimension

$$\Gamma(\bar{q}, \Delta t) = \sum_{\Lambda_i} P_i(\Delta t)^{\bar{q}} \approx (\Delta t)^{\tau(\bar{q})} \Rightarrow \tau(\bar{q}) = (\bar{q}-1)D_{\bar{q}} \Rightarrow D_{\bar{q}} = \frac{1}{\bar{q}-1}\lim(\log \sum p_i^{\bar{q}} / \log r)$$

Multifractal Spectrum Function

$$f(a) = \bar{q}a - (\bar{q}-1)D_{\bar{q}}$$

$$q_{sens} = 1 + \frac{a_{\max} a_{\min}}{a_{\max} - a_{\min}} \Leftarrow f(a_{\min}) = f(a_{\max}) = 0 \Leftarrow f(a)$$

The entropy production process is related to the general profile of the attractor set of the dynamics. The profile of the attractor can be described by its multifractality as well as by its sensitivity to initial conditions

(q_{rel})

$$q_{relax} = \frac{s-1}{s} \Leftarrow \log C(\tau) = a + s\log(\tau)$$

Macroscopically, the relaxation to the equilibrium stationary state of some dynamical observable O(t) is related to the evolution of the system in phase space

TSALLIS *q*-TRIPLET – *Theoretical Estimation*

Multifractal Spectrum *f*(*a*) – Generalized Dimension *D*(*q*)

For the estimation of the multifractal spectrum function we need three parameters (a_0, q, X). According to Arimitsu and Arimitsu (2001) we can estimate these parameters by using the equations:

Multifractal Spectrum Function

$$f(a) = D_0 + \log_2[1-(1-q)\frac{(a-a_o)^2}{2X/\ln 2}]/(1-q)^{-1} \qquad (\bar{q}=2) \qquad \tau(\bar{q}) = (\bar{q}-1)D_{\bar{q}}$$

Intermittency Exponent

$$\mu = 1+\tau(\bar{q}=2) \qquad \tau(\bar{q}) = \bar{q}a_0 - 1 - \frac{2X\bar{q}^2}{1+\sqrt{C_{\bar{q}}}} - \frac{1}{1-q}[1-\log_2(1+\sqrt{C_{\bar{q}}})] \qquad \frac{1}{1-q} = \frac{1}{a_-} + \frac{1}{a_+}$$

$$\left.\begin{aligned} \sqrt{2X} &= \left[\sqrt{a_0^2+(1-q)^2} - (1-q)\right]/\sqrt{b} \\ b &= (1-2^{-(1-q)})/[(1-q)\ln 2] \end{aligned}\right\}$$

p - model

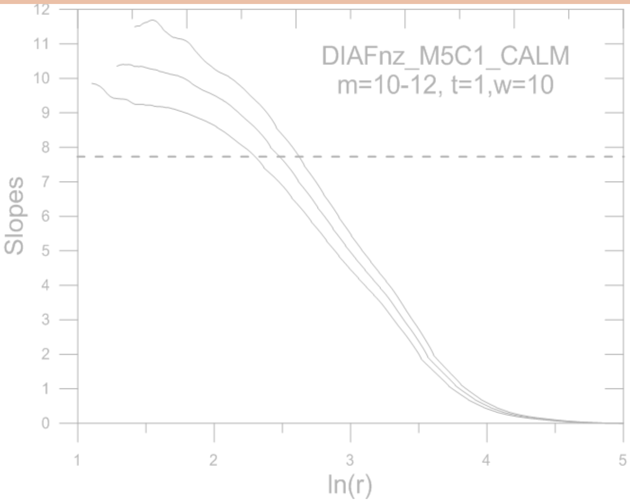
The p-model is a one-dimensional model version of a cascade model of eddies. The p-model was introduced to account for the occurrence of intermittency in fully developed turbulence. The best nonlinear fit of the generalized dimension function is represented by

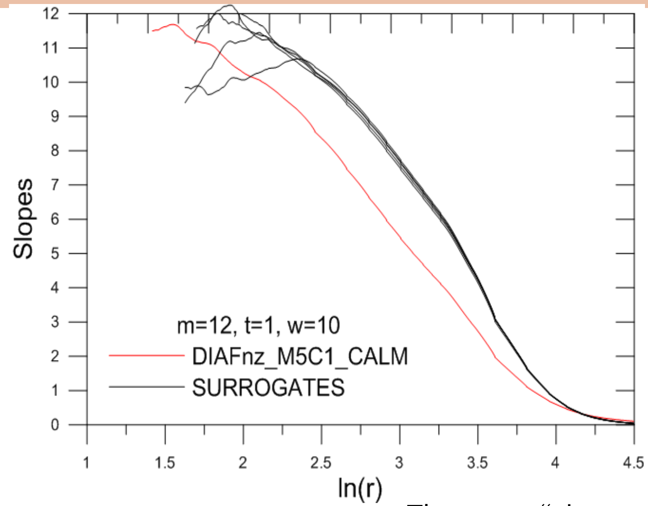
$$D_{\bar{q}} = \log_2\left[p^{\bar{q}} + (1-p)^{\bar{q}}\right]/1-\bar{q}$$

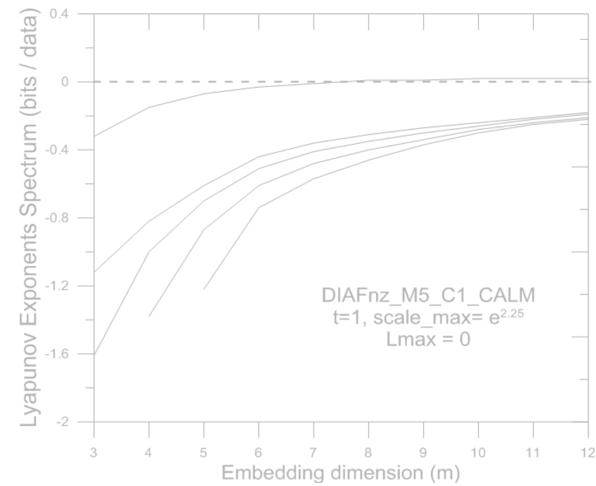
When p = 0.5, then we have a Gaussian Process

Results - *Comparing Calm and Shock Period*

Calm Period – SOC (Slopes, *D* = 12 (*m*=12) – Lyapunov Exponents, Lmax = 0)



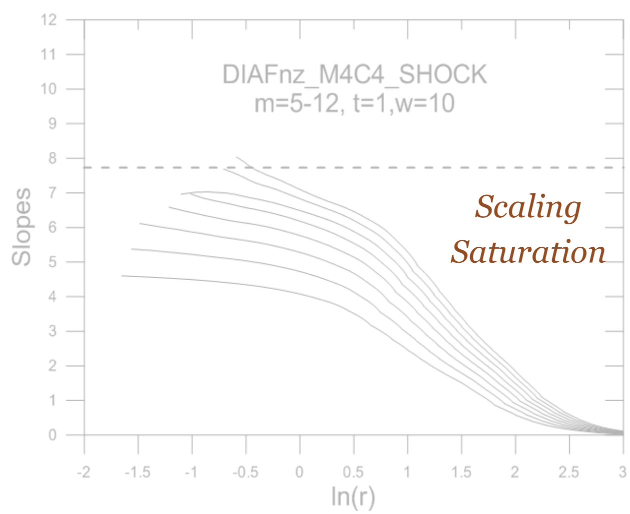


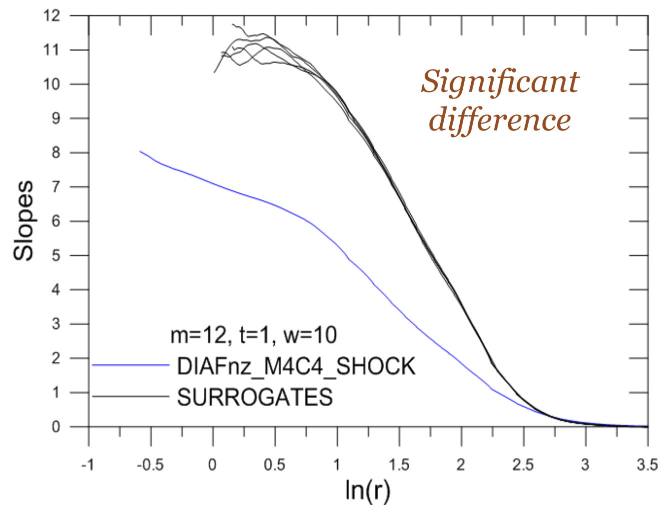


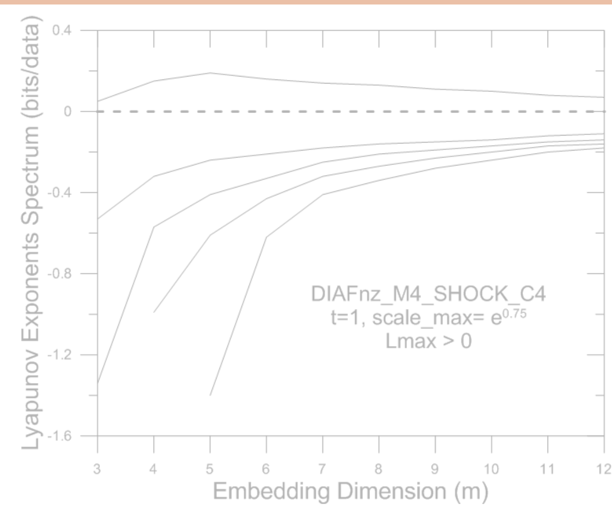
PHASE TRANSITION

The term ‘‘phase transition process’’ must be understood as a ‘‘metaphase transition’’ process and it is used in order to characterize the change of the metaequilibrium critical state of the wind dynamics from the high dimensional solar SOC state to the low dimensional solar chaos state.

Shock Period – CHAOS (Slopes, *D* = 7.8 (*m*=12) – Lyapunov Exponents, Lmax > 0)

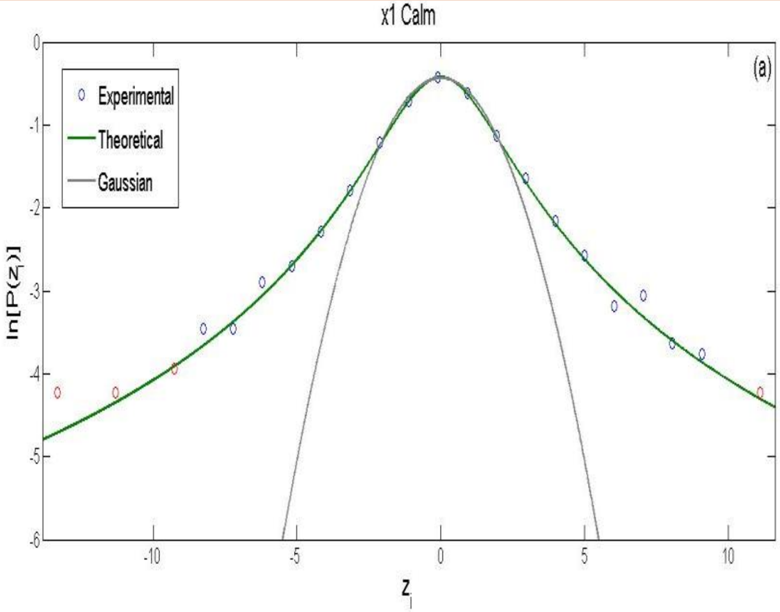


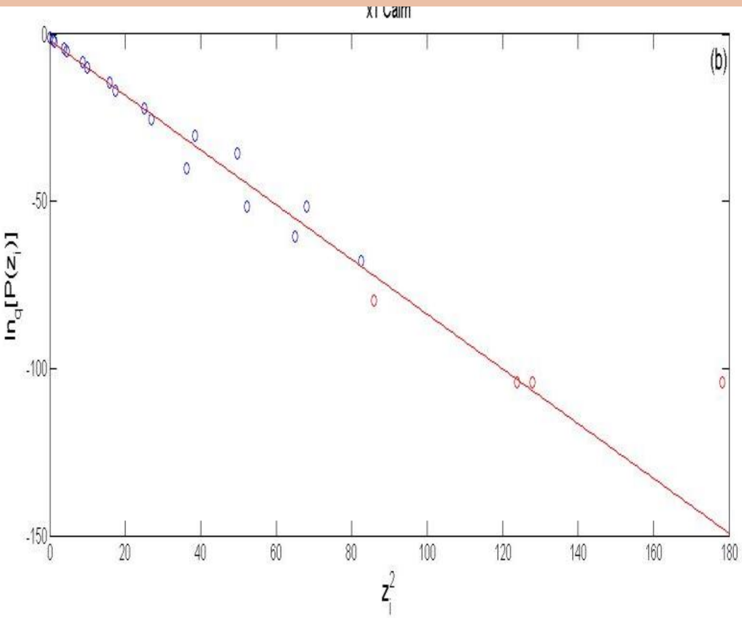




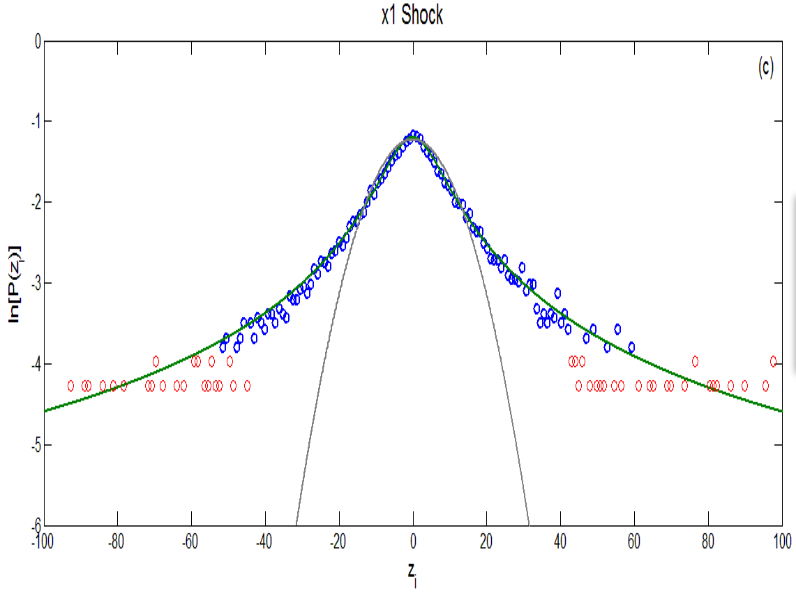
Results - *Comparing Calm and Shock Period*

***Calm Period* – q_stat = 1.38**

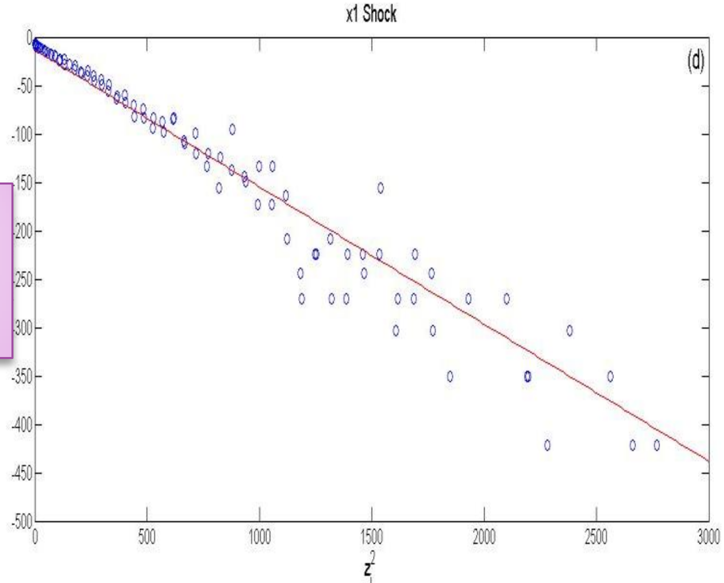




***Shock Period* – q_stat = 1.64**

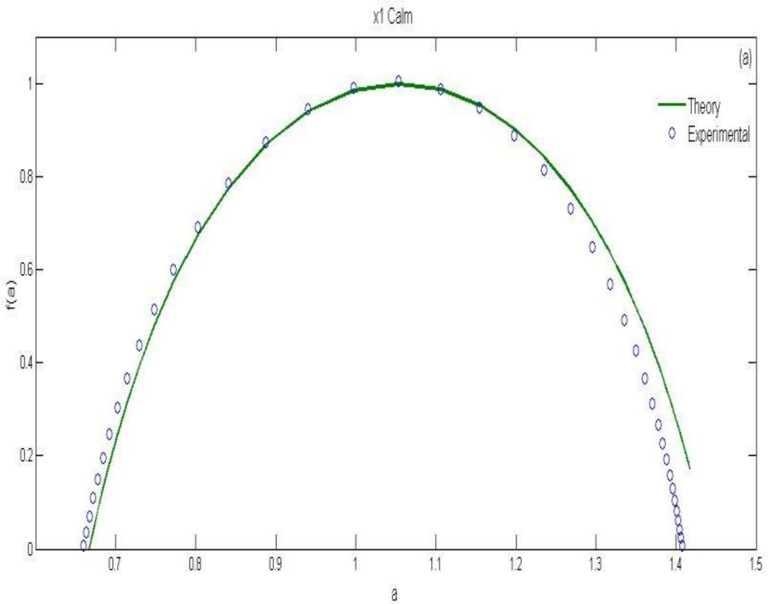


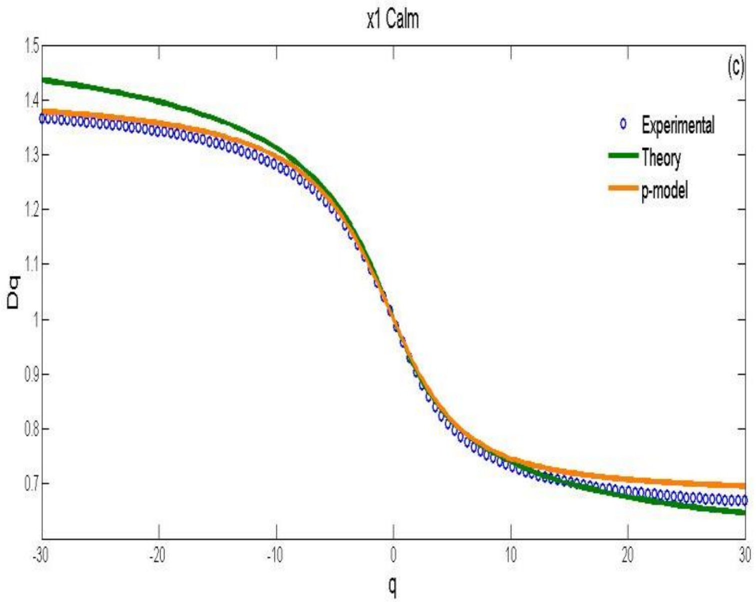
Strengthening of non-gaussian and Tsallis non-extensive profile



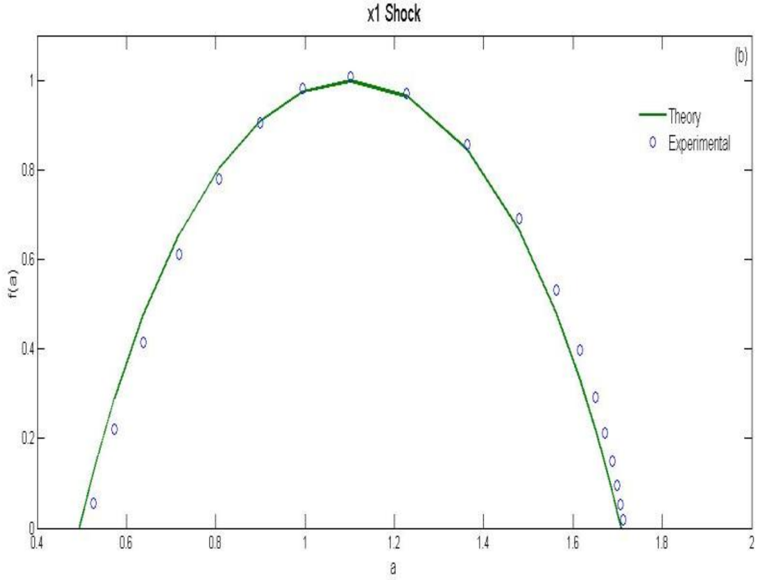
Results – Comparing Calm and Shock Period

Calm Period – q_sens = - 0.2422 (Singularity Spectrum – Generalized Dimension)

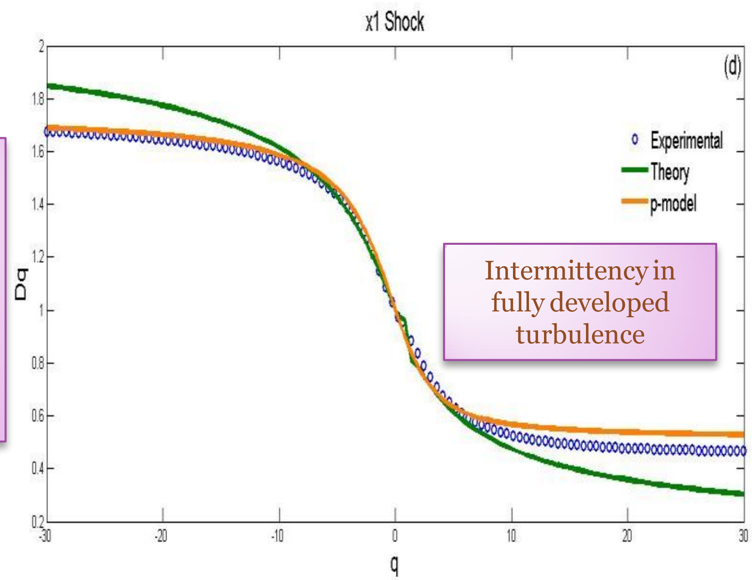




Shock Period – q_sens = 0.2731 (Singularity Spectrum – Generalized Dimension)

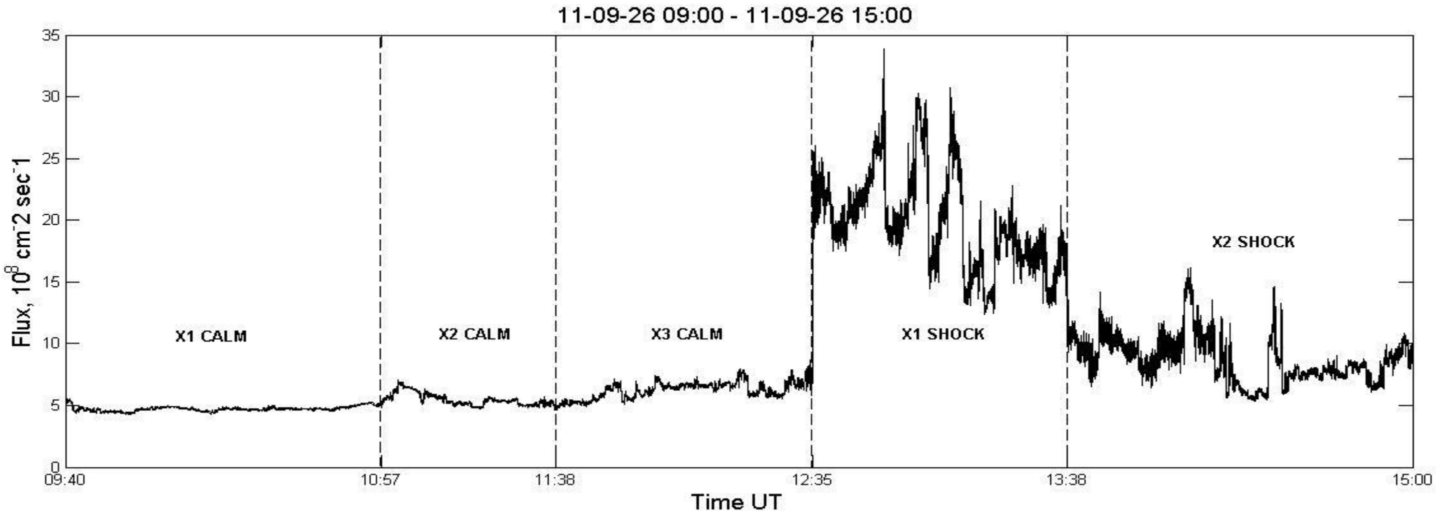


Stronger instability and growth of q-entropy production, due to increase of the multifractality

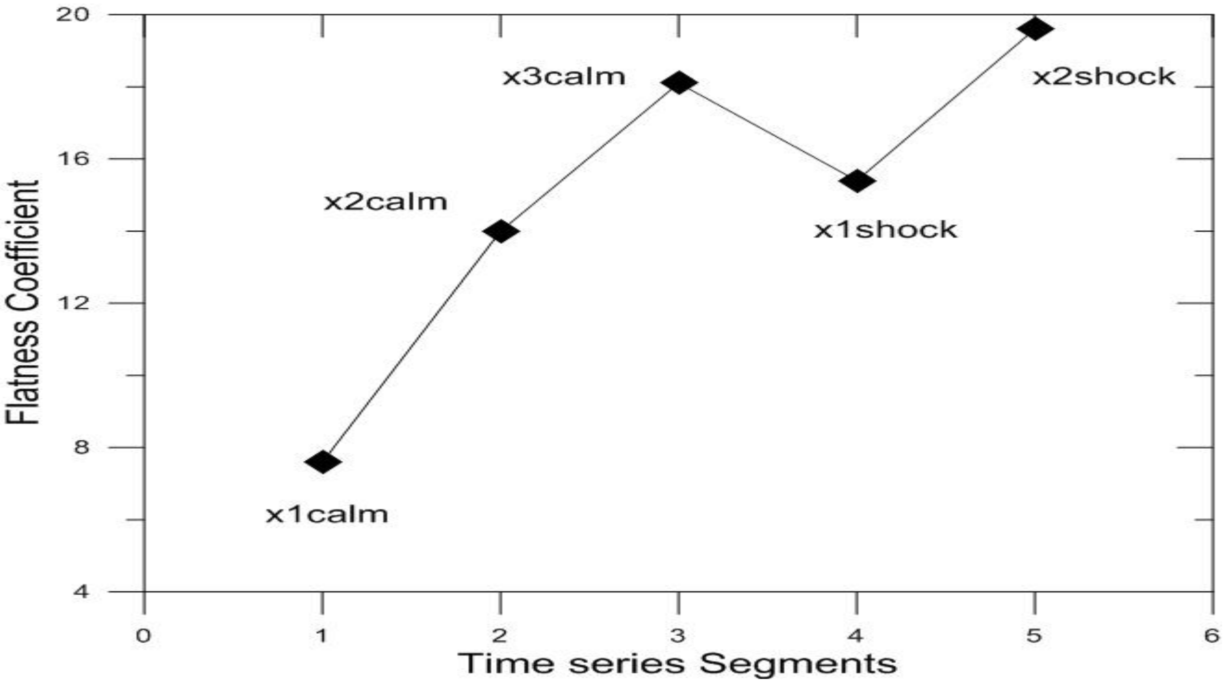


Intermittency in fully developed turbulence

Results - Studying the Transition



Flatness Coefficient F



Increase of long range correlations, non-Gaussian and intermittent character

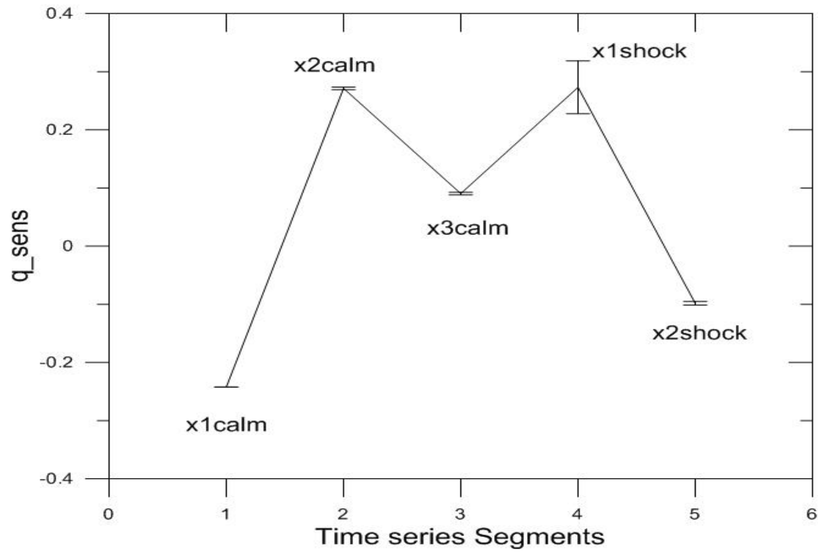
When F = 3, then we have a Gaussian Process

$$F = \frac{< \delta B_\tau(t)^4 >}{< \delta B_\tau(t)^2 >^2}$$

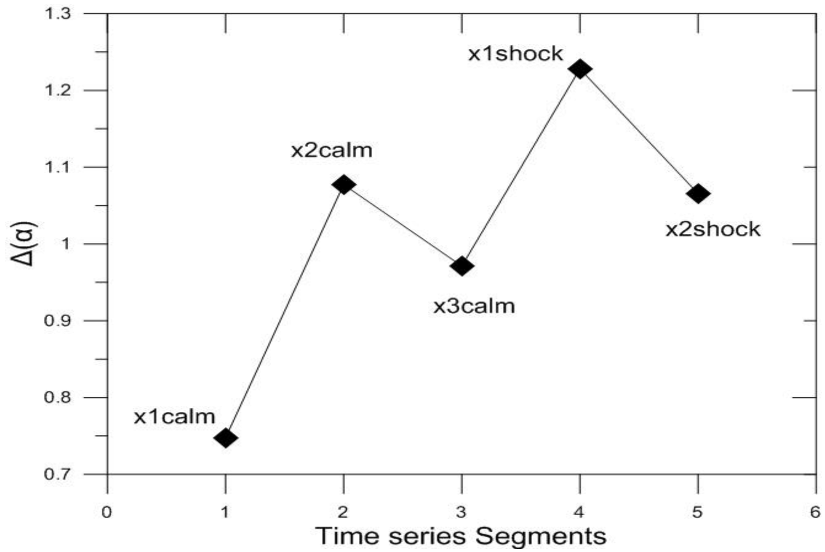
$$\delta B_\tau(t) = B(t+\tau) - B(t)$$

Results - Studying the Transition

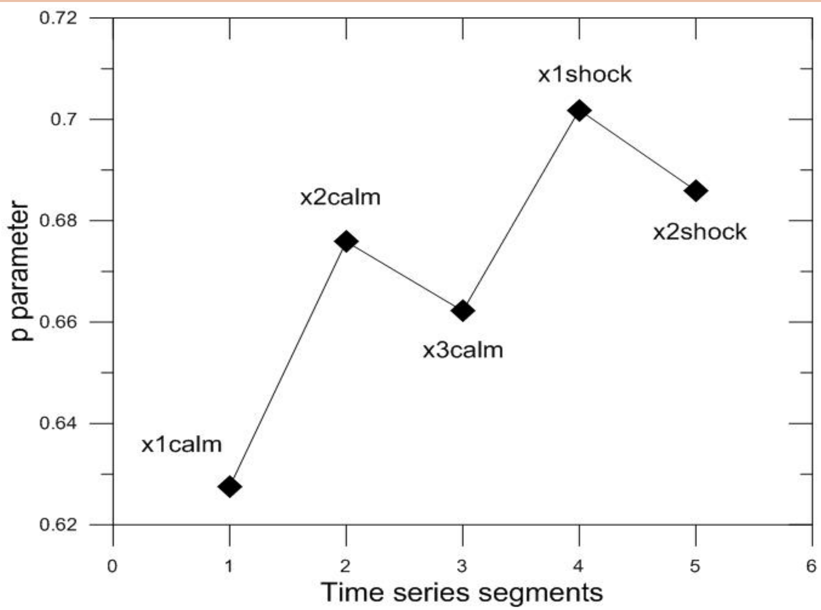
q_sens



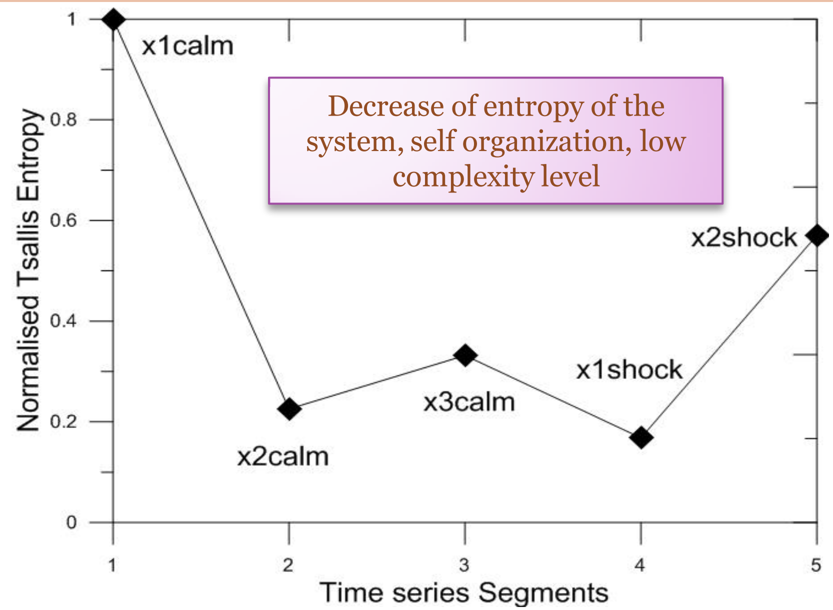
Multifractal range - Δ(a)



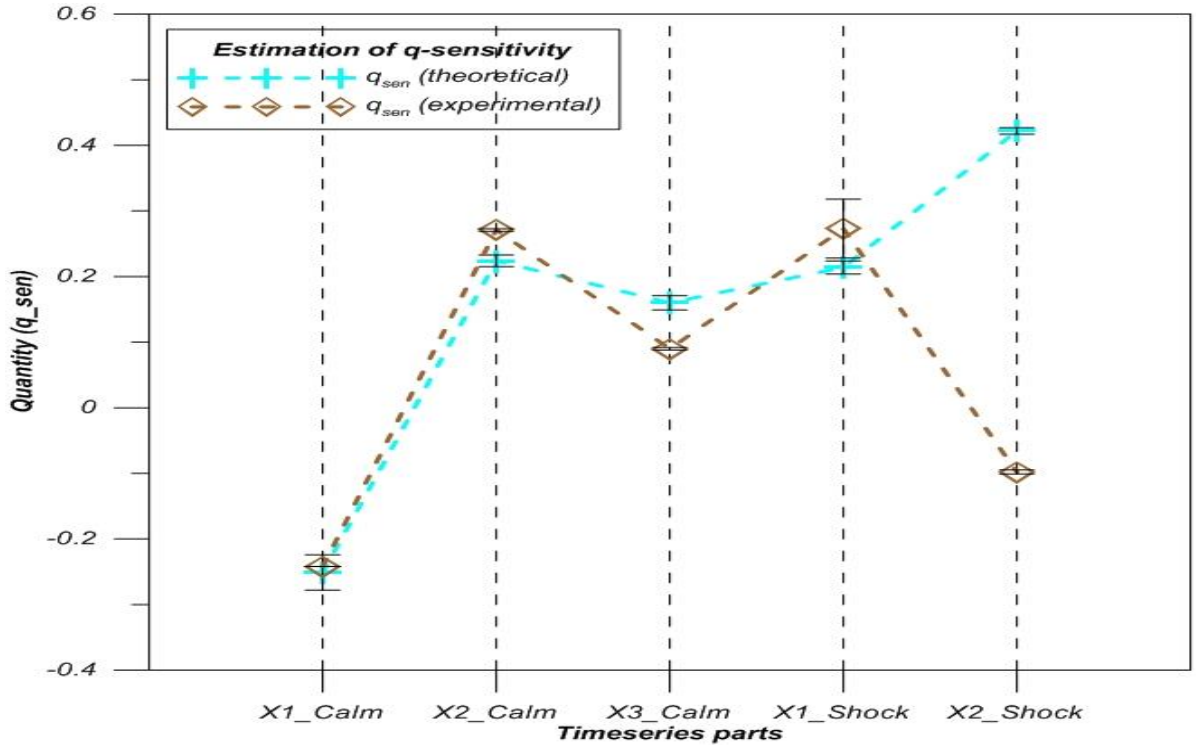
p – parameter



Tsallis entropy



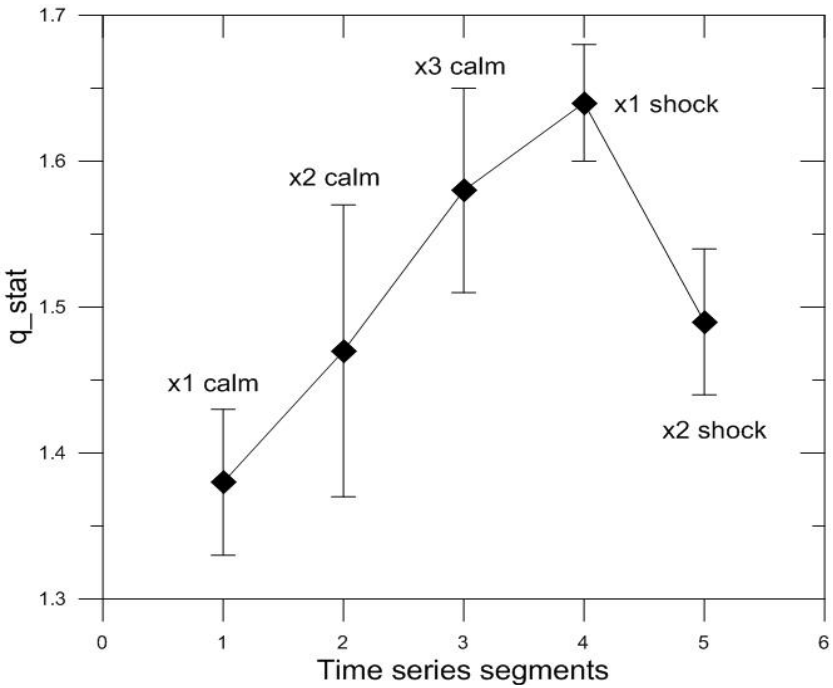
Results – Studying the Transition

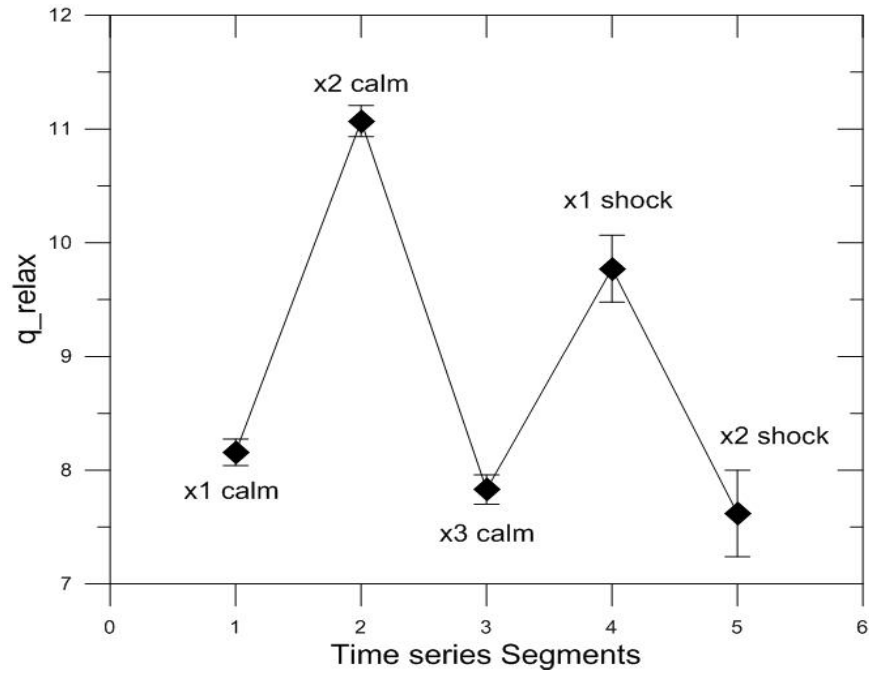


Timeseries	μ *	a_0	X *	q_sen * Theoretical	q_sen Experimental
X1 Calm	0.096	1.054±0.001	0.110	-0.251±0.027	-0.2422 ± 0.00009
X2 Calm	0.18	1.103±0.001	0.212	0.224±0.009	0.2713± 0.0024
X3 Calm	0.163	1.093±0.001	0.191	0.160±0.011	0.0904 ± 0.0022
X1 Shock	0.177	1.101±0.001	0.208	0.214±0,010	0.2731 ± 0.0455
X2 Shock	0.255	1.147±0.001	0.303	0.422±0.005	-0.0982 ±0.0031

Results - Studying the Transition

q_stat	q_relax





Gradual Development of non-Gaussian, non-extensive dynamics

Strengthening of non-Gaussian, non-extensive dynamics (x1 calm vs x1shock)
Large fluctuations

Summarizing Results - *3 Shock Events*

Table 2.						
Indices	**Shock Event**					
	A Calm	**A Shock**	**B Calm**	**B Shock**	**C Calm**	**C Shock**
q_{rel}	3.12	3.57	12.89	10.78	8.158	9.772
q_{stat}	1.37	1.52	1.41	1.78	1.38	1.64
q_{sen}	0.0796	0.0217	-0.4384	-0.0071	-0.2422	0.2731
$\Delta\alpha$	1.0106	0.9061	0.7023	0.9707	0.7478	1.2045
$\Delta(D_q)$	0.9493	0.8861	0.6661	0.9705	0.6981	1.2106
Tsallis Entropy	15.47	20.62	199.8	48.05	111	20

q_{stat} increases passing from calm to shock period in all cases. However the other two indices changes depending on the shock event.

Summary of Results

•A phase transition takes place from calm to shock period. In particular, as the estimation of slopes of the correlation dimension and Lyapunov exponent spectrum showed, the calm period corresponds to a self organized critical state while the shock state to a low dimensional chaotic state.

• Enhancement of the non-Gaussian character of the dynamics, as the Flatness coefficient *F* clearly increases to values much higher than 3.

• Clear non extensive statistical character of solar wind was observed during the calm or shock periods.

• The Tsallis *q*-triplet parameters increase from calm to shock period.

• The multifractal character is strengthened passing from the calm to the shock period, as it is concluded by the profile of singularity spectrum f(α) and the width variation from the calm to the shock state Δ(a).

•The parameter *p* of the *p*-model estimated from the nonlinear best fitting of the data was found to increase passing from calm to shock period.

• Strong reduction of Tsallis entropy production was observed 60-90 minutes before the main shock event.

•The intermittency exponent (μ) also increase passing from the calm to shock state.

•Faithfull coincidence can be observed between the experimentally estimated singularity spectrum f(α) and the q_{sen} parameter values and the correspondent values estimated using the Tsallis *q*-entropy principle.

•Fluctuations of all parameters were found, a result which indicates the presence of fracton dynamics.

• The study of three shock events showed changes in Tsallis *q*-triplet statistics. Only, the q_{stat} index increases in all cases. This result needs further investigation.

Conclusions

- Existence of a dynamical non-equilibrium phase transition process related to the solar wind shock event from the original solar wind complex calm state to states which include enhancement of self organization and intermittency.

- Possible precursory phenomena observed minutes before the main shock event.

- The results presented before can be connected with Zelenyi and Milovanov (2004) hypothesis, that the complex character of the solar wind plasma can be described as non-equilibrium (quasi)-stationary states (NESS) having the topology of a percolating fractal set. These scales include multi-scale interactions of fields and particles (currents) and can be related to the simultaneous development of numerous instabilities interfering with each other.

- Finally, the results indicate that the solar wind plasma system can include fracton excitations and fracton dynamics where fracton formations are waves on fractal structures. Fracton dynamics can cause the oscillations of statistical parameters observed during shock events development.

THANK YOU

for your attention