Statistical Approaches of Small-scale Coronal Heating

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with Sebastien Galtier, Marco Velli, Jean-Claude Vial and Philippe Lemaire

Why are we doing statistics ?

Why are they useful :

- small-scales too small to be observable
- too wide range of length and time scales
- can be linked to turbulence theories

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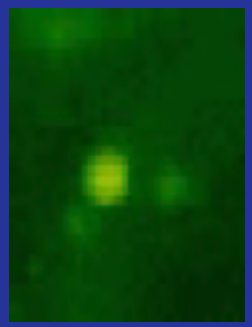
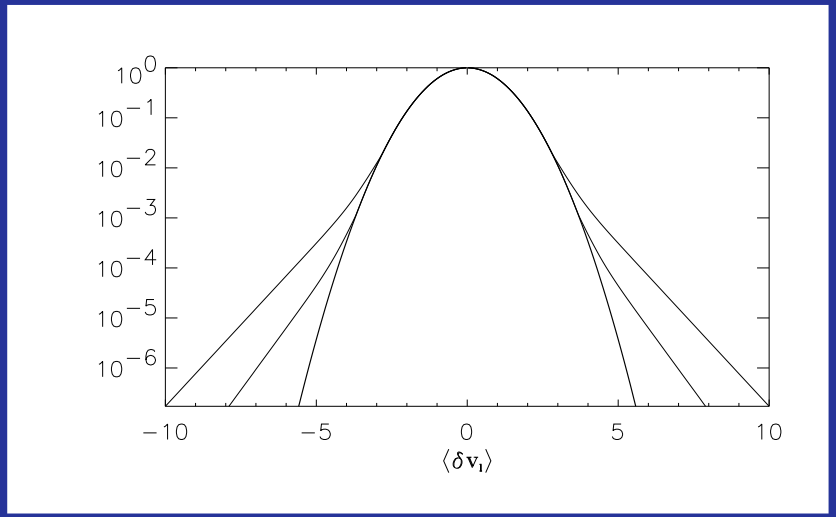
What are our goals :

- find new signatures of heating in turbulence-generated small-scale structures
- better understanding of coronal heating
- numerical and observational tests of theories of MHD turbulence and intermittency

Statistical approach

- Observe and simulate coronal heating “events” (intermittent brightenings...)
- Get statistics (histograms, structure functions...)
- Compare observations and simulations,
  and compare to statistical signatures predicted by theories
  (turbulence, intermittency)





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- Define and detect events :
  - separate (temporally and spatially)
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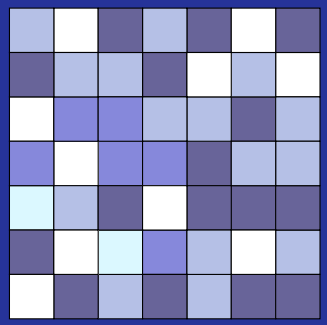
- Get significant statistics :
  - lots of observations
  - lots of simulations (fast $\Longrightarrow$simplified MHD)
  - statistics other than histograms are harder to get
- And...
  - A signature is a clue, not a proof

    (“power-law spectra” of most landscape photographies)

A cellular automata model

Why cellular automata ?

Principle : system evolution by local interactions between a quite small number of "cells".
A lot of models for the solar corona exist, from Lu & Hamilton (1991) to Islisker et al. (2000).



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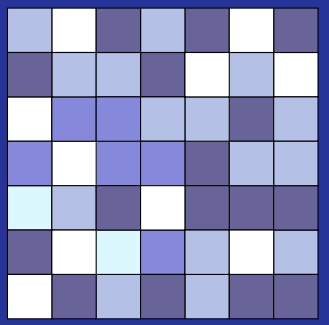

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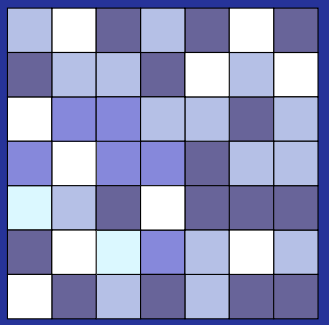
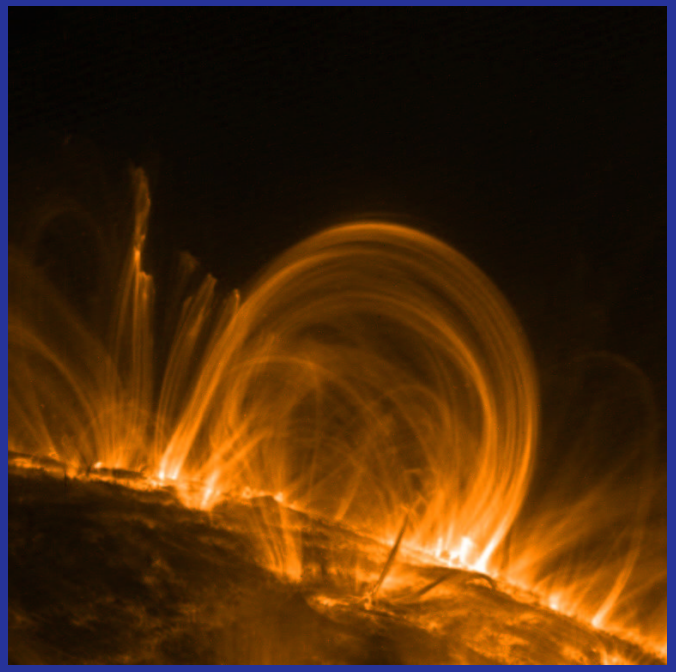
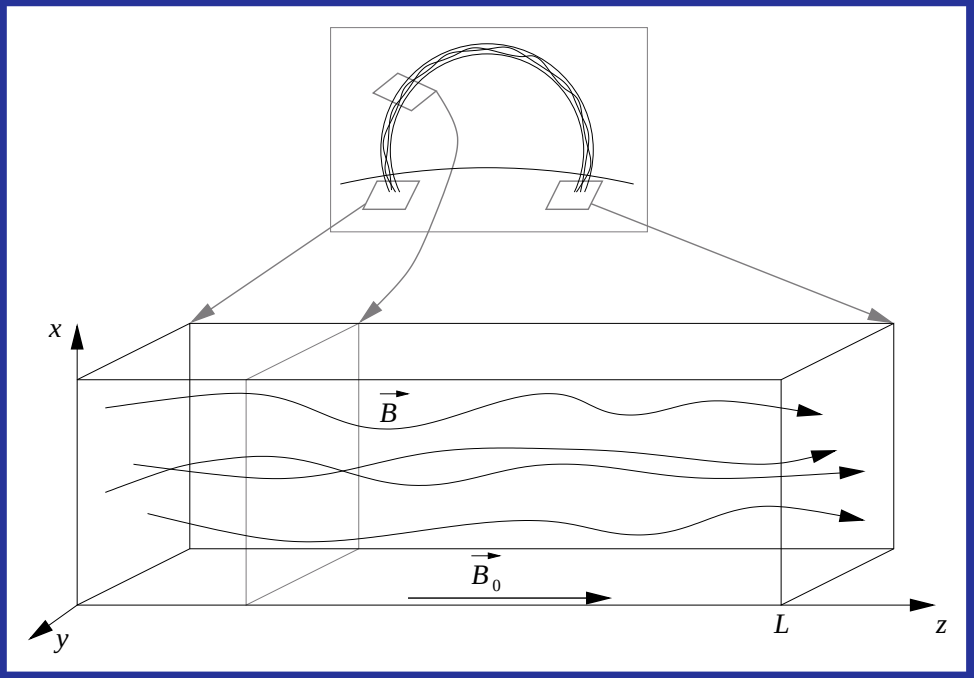


Fast, well-adapted to statistical analysis...

...but the rules of evolution often lack of physical bases.

The model





- 3D $64^2 \times 30$, loop geometry and dominant $\vec{B}_0$
- Alfvén waves reflecting on the photosphere
- “Photospheric” loading in $k^{-\alpha}$ (Roudier et al. 1986)
- Dissipation by avalanches (threshold : electric current)

The model (2)

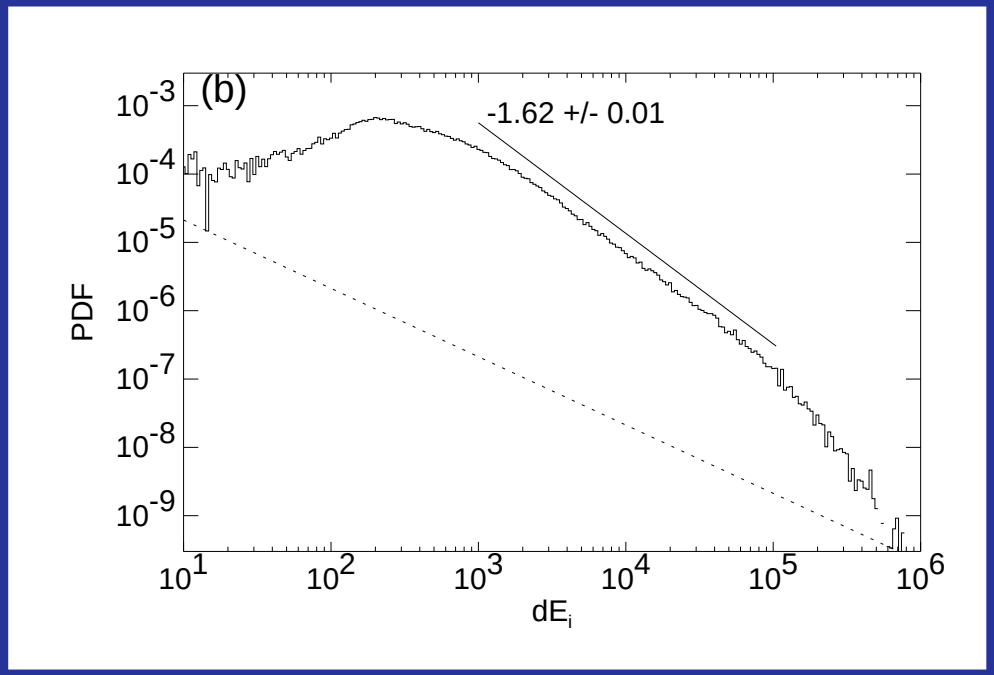
RMHD-based with non-linear terms modeled through on-off mechanism (giving SOC-like avalanches)
$\Longrightarrow$Very fast (suitable for statistical approach)

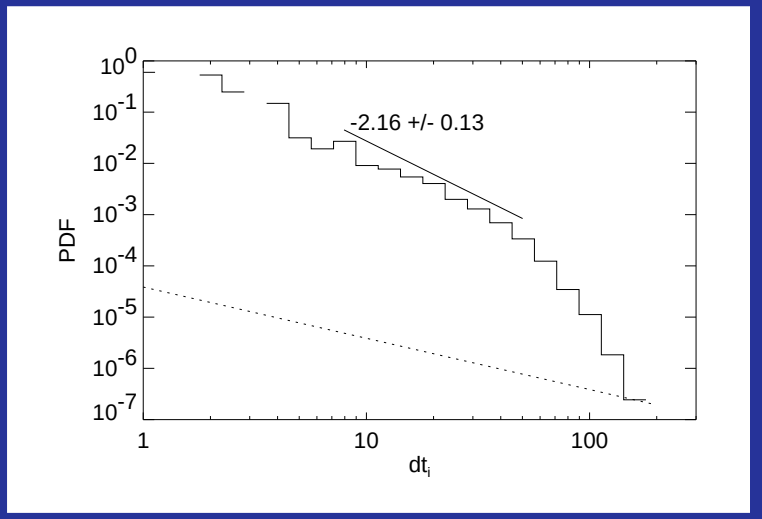
For detailed results, see :

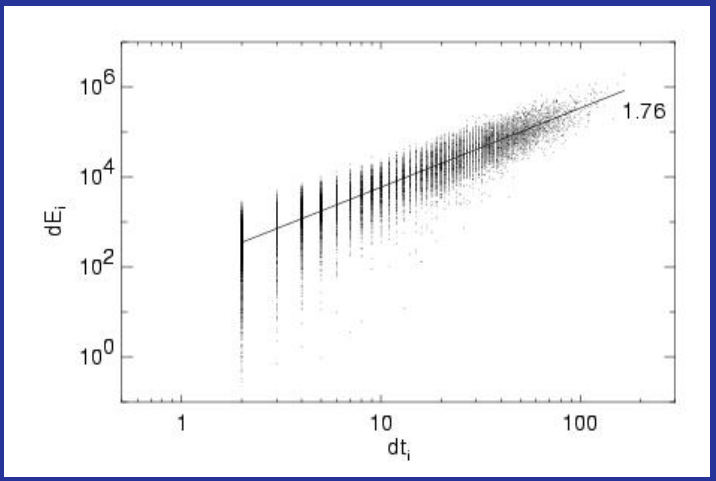
- V. Aletti, M. Velli, K. Bocchialini, G. Einaudi, M. Georgoulis, J.-C. Vial, ApJ **544**, 550 (2000)
- E. Buchlin, V. Aletti, S. Galtier, M. Velli, G. Einaudi, J.-C. Vial, A&A, **406**, 1061 (2003)

Model results (1)

Power-law PDFs of event energy, PDF of event duration, and correlations between *e.g.* energy and duration



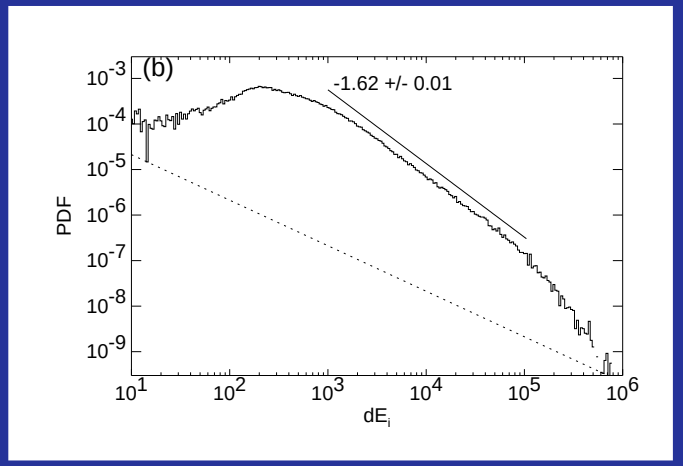




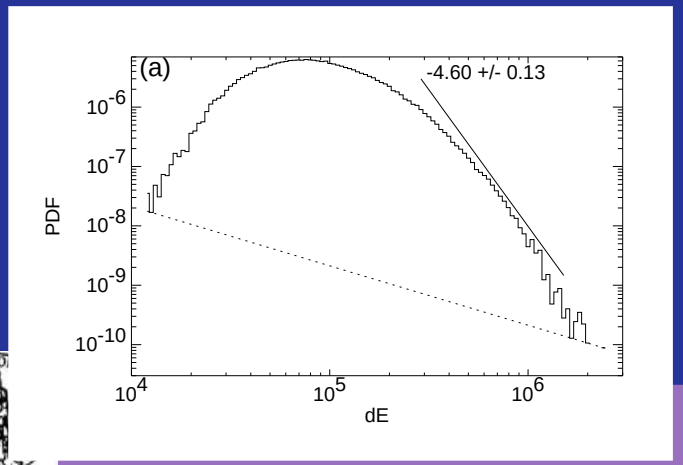
Model results (2)

Clues for possible observational biases

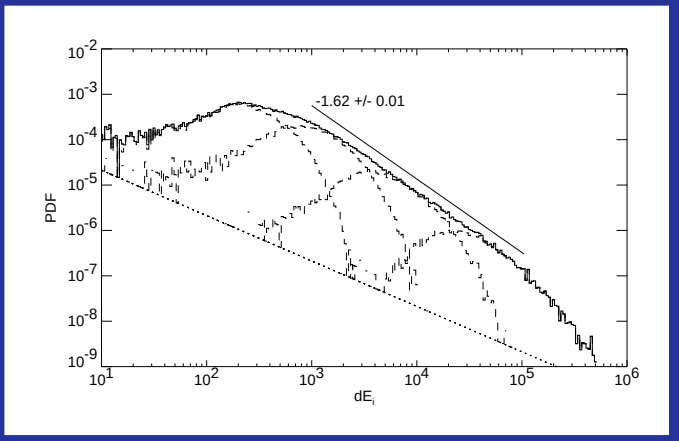
Spatial :



vs.

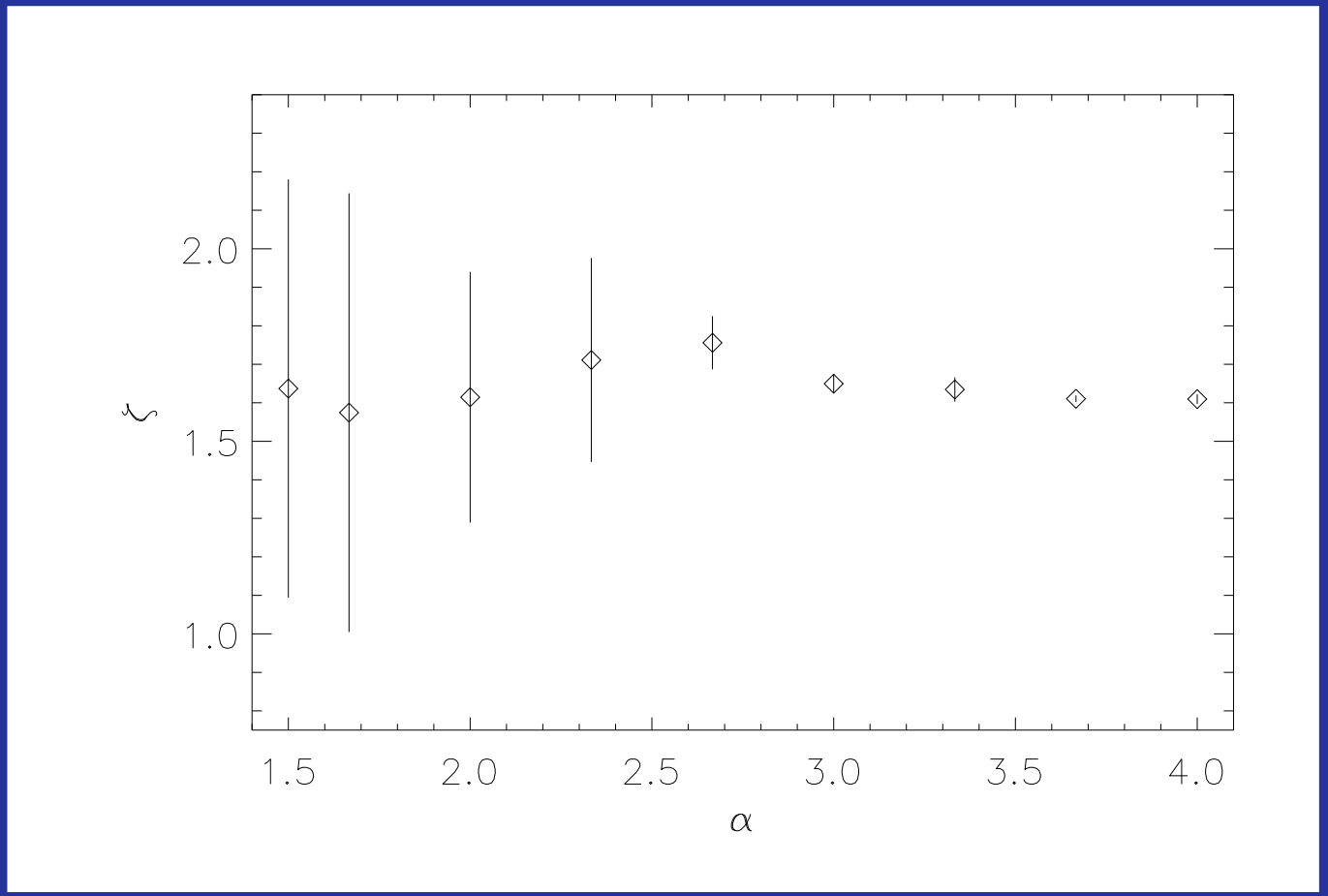


Observation duration :



Model results (3)

SOC-like "universality" of PDF slopes (here : as a function of model loading spectrum index)



Data analysis

Statistical data analysis

$\Longrightarrow$search for observational signatures of turbulence and intermittency in observational data ?

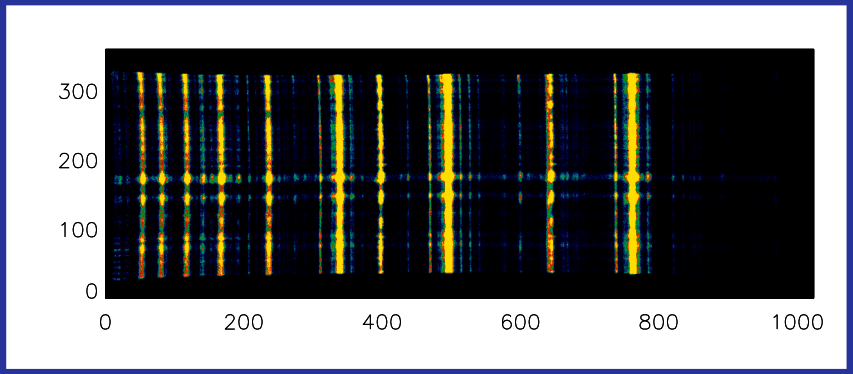
Requirements for the data :

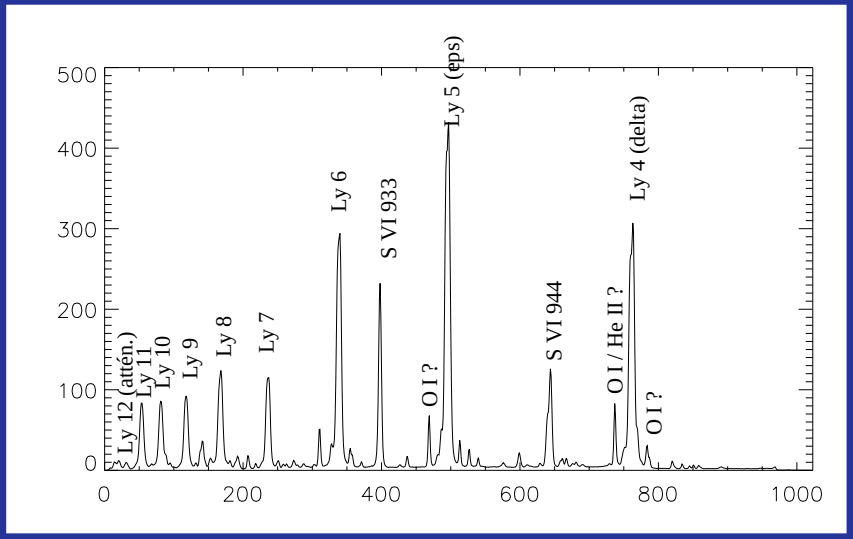
- of course, good quality
- large amount of data for each observation
- large number of observations

SUMER Full Sun data

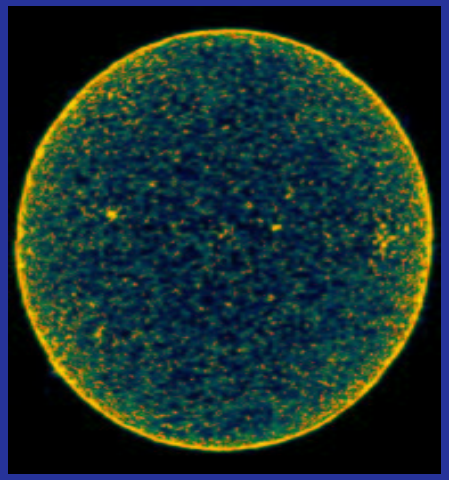
Observations by Philippe Lemaire, april–october 1996.

- 8 rasters per image
- 36 images
- "Moments" computed on-board :
  - 0 : Intensity (max) S VI 933
  - 1 : Doppler shift S VI 933
  - 2 : Width S VI 933
  - 3 : Intensity Ly ϵ
  - 4 : Intensity S VI 944
- Some reference spectra (whole detector)

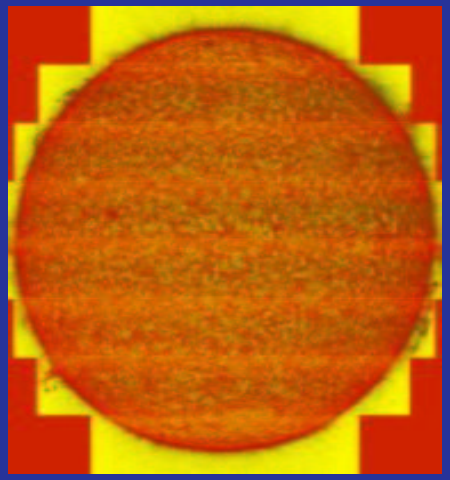




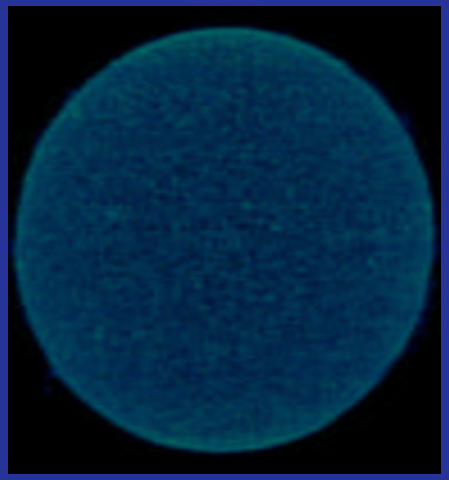
Full Sun reconstructed images



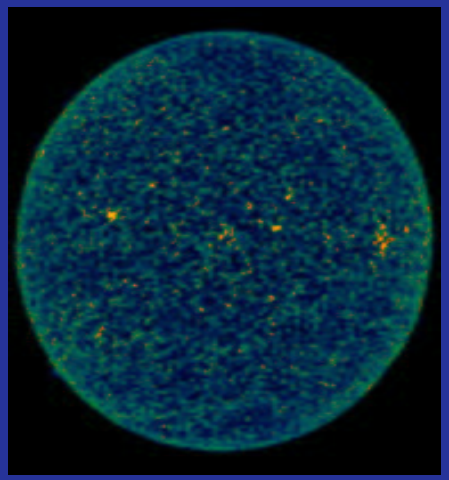
S VI 933 I



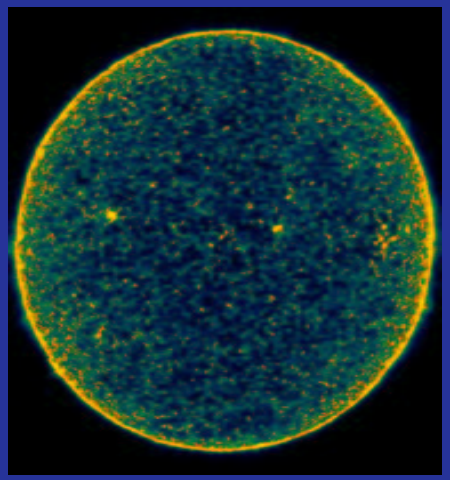
S VI 933 V



S VI 933 W

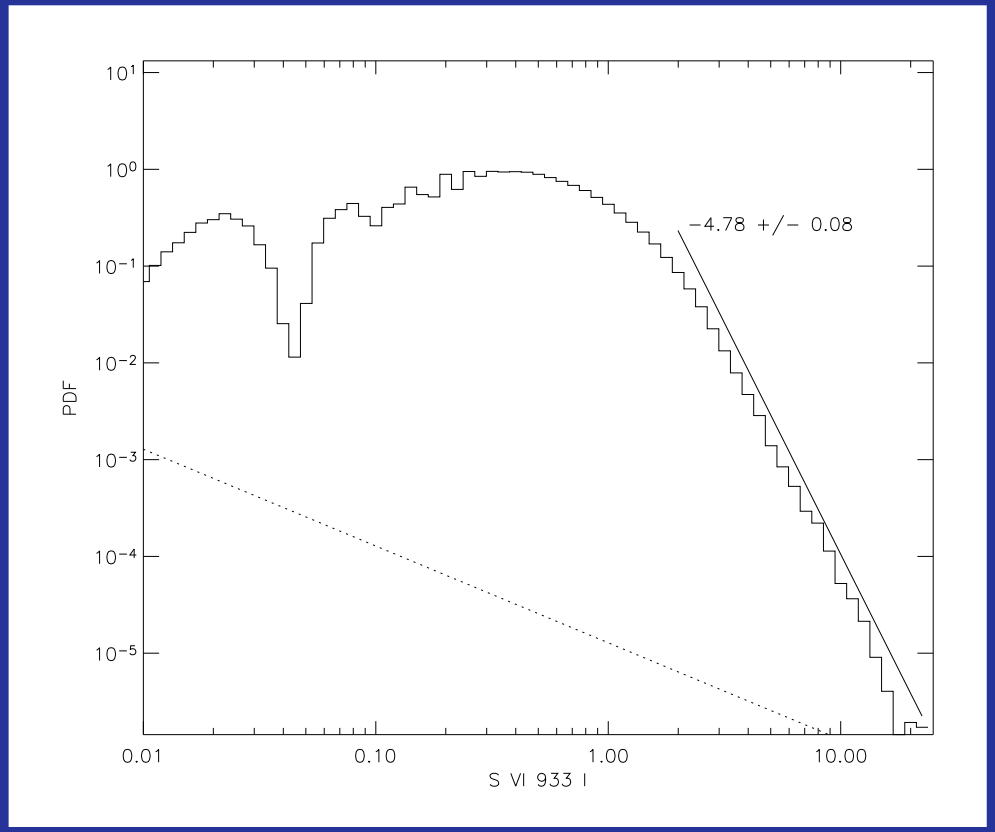


Ly ϵ I



S VI 944 I

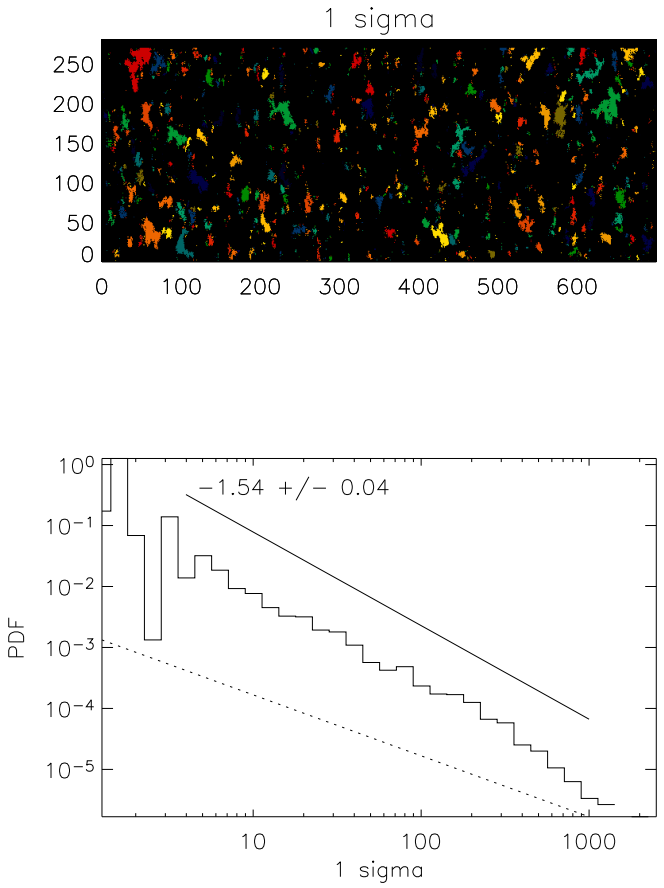
Histogram of pixel S VI 933 intensity



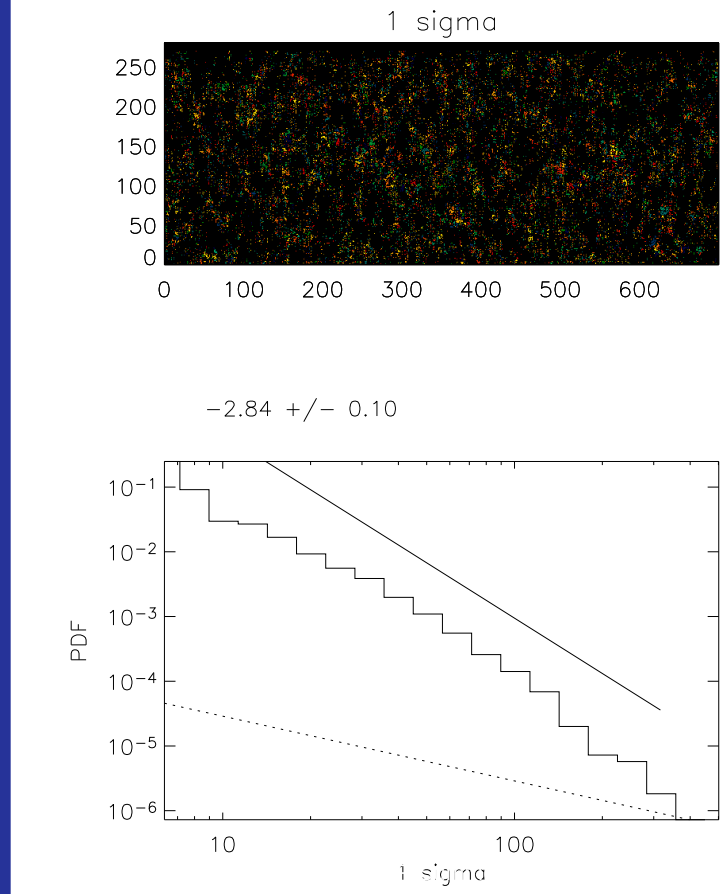
Histograms of events

Like in Aletti et al. 2000 (EIT) : one “event” = a connex part of the image above a threshold.

S VI 933 intensity :

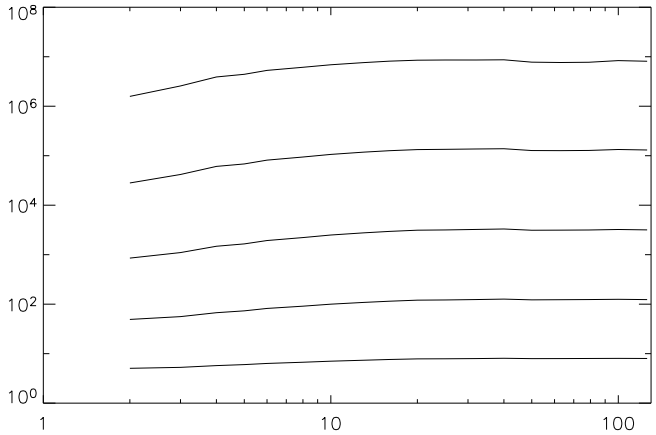


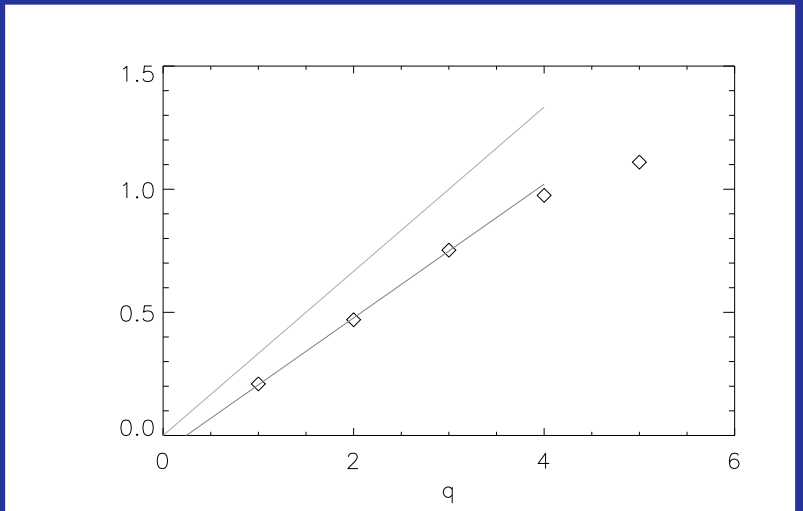
S VI 933 velocity :



Structure functions and exponents

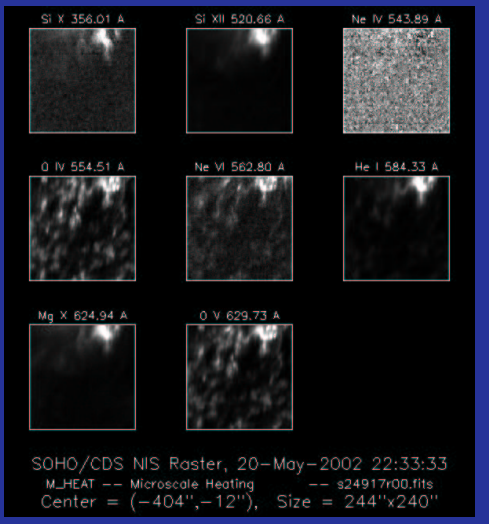
For intensity :

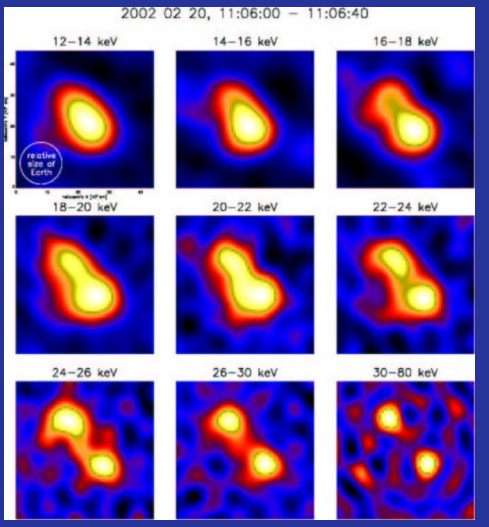




Other data that can be used

- CDS (MEDOC campaign, May 2002), but need of more observations for good statistics
- RHESSI, but small flares can only be visible when no large flares (Image reconstruction artefacts)



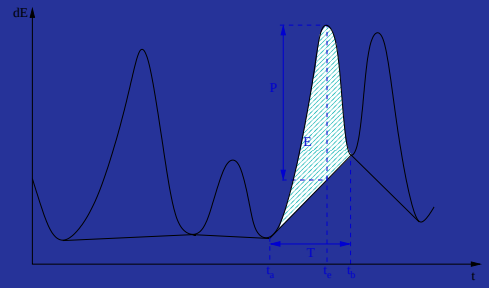


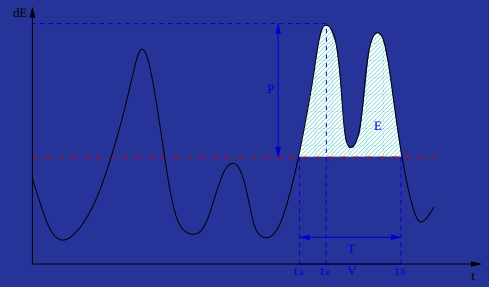
But what is an event ?

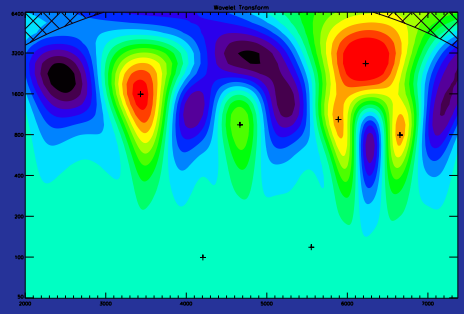
Some definitions used

Candidates for a definition :

- peak in energy dissipation time series (from a local minimum to the next one)
- connex part of image or time series above a threshold
- local maximum in a time series' time-frequency plane (wavelets)



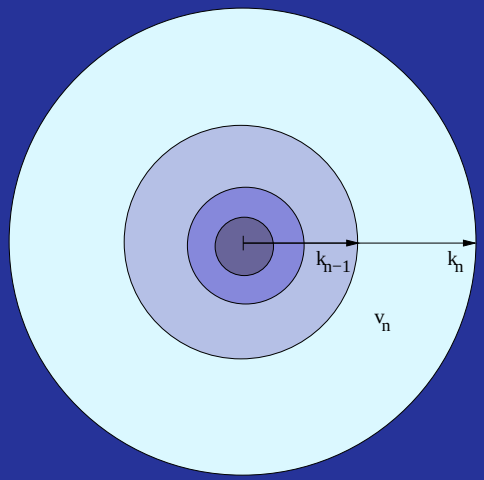




Non-exhaustive ! ...open to suggestions

Test on shell-model time series data

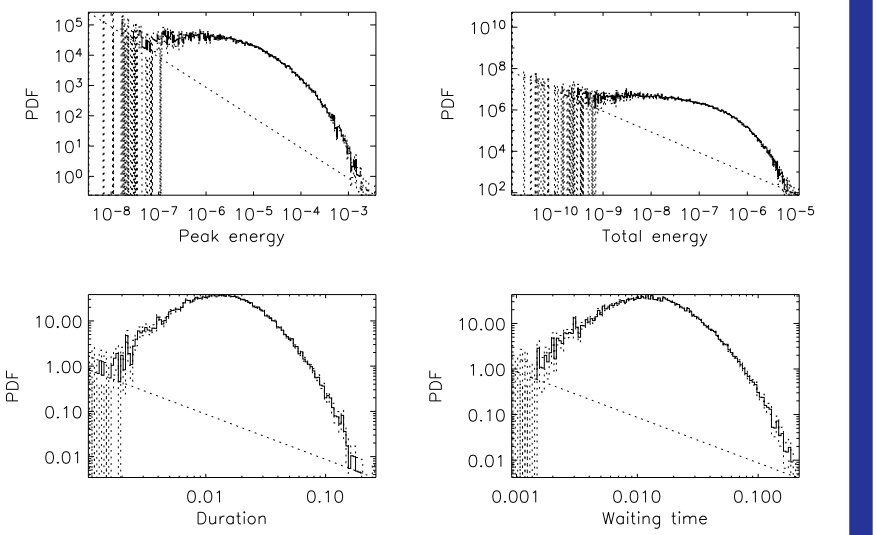
- 1D model with reduced number of modes : concentric shells in Fourier space, separated by a factor 2 of wavenumber. Inspired from Giuliani et al. 1998.
- Local interactions between shells (up to the 2nd-neighbors), modelling the non-linear terms of MHD, with strict conservation of energy, helicity and magnetic helicity.

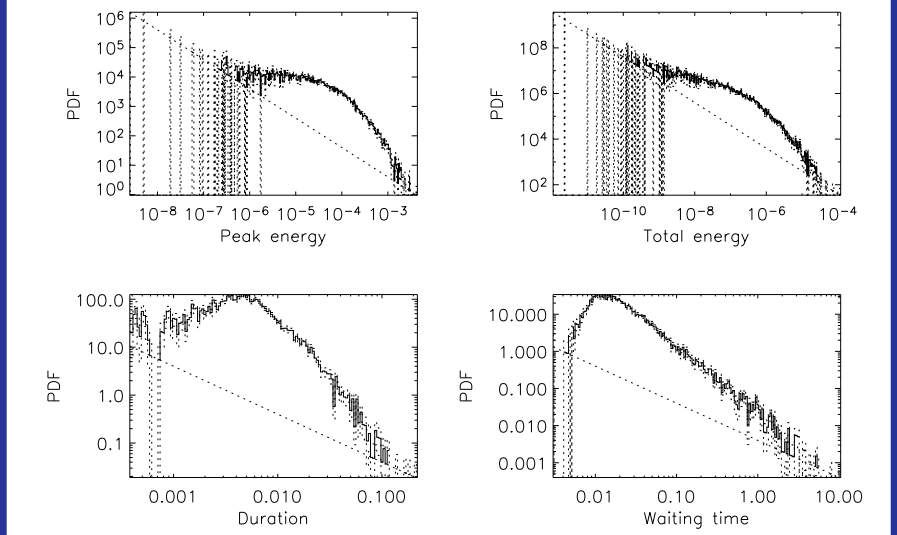


$\Longrightarrow$Energy dissipation time series

Results

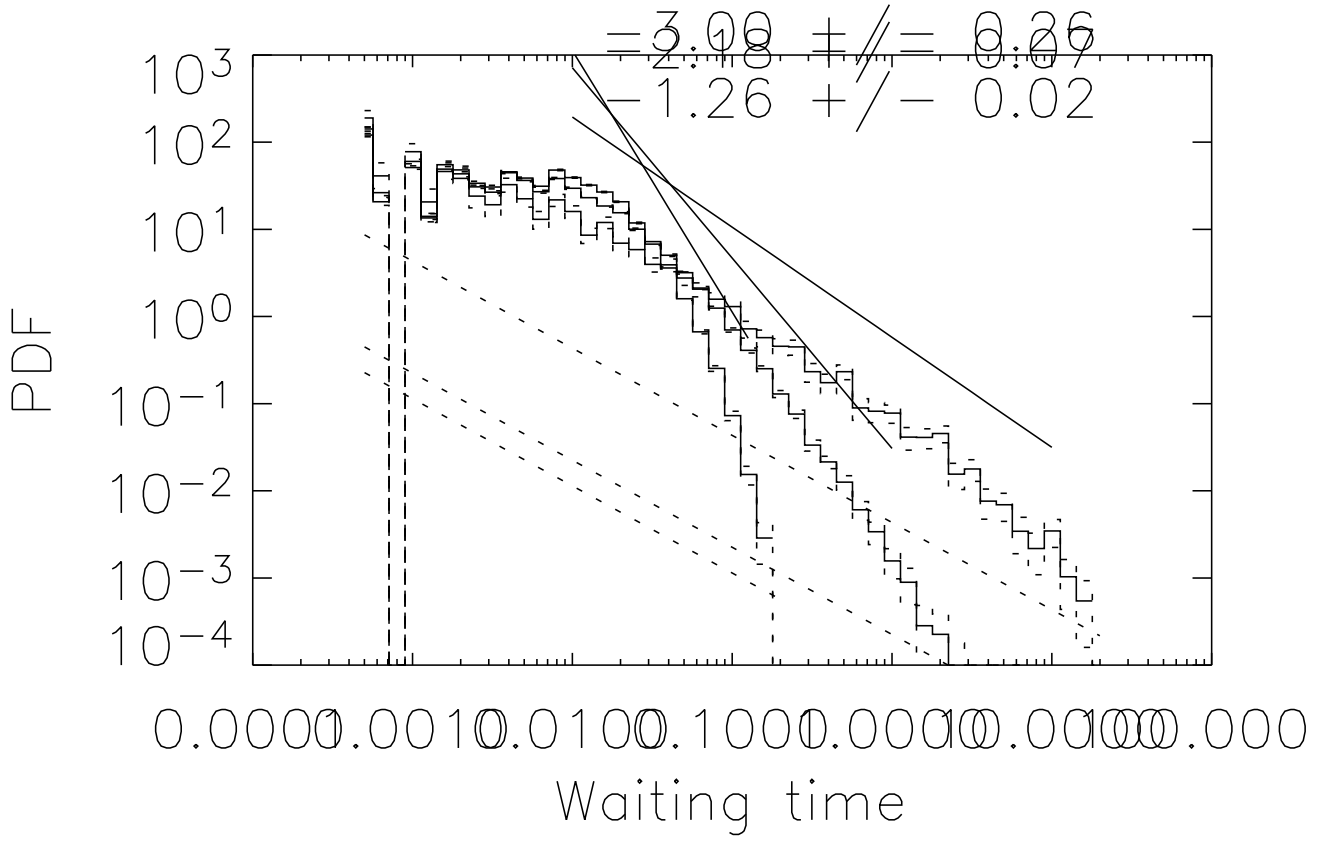
Distributions, for peak and threshold definitions :





Results

For wavelets definition :



Discussion

- The choice of definition has an influence on statistics. No straight-forward choice of definition
- Structure functions act directly on fields, do not depend on event definition
- Also looking for other statistics (open to suggestions !), *i.e.* more clues
- Need more tests to constraint models and to compare them to observations : line emission, particle acceleration statistics...

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