Simplified simulations of MHD in a coronal loop

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SOHO 15 – Coronal heating, 07 September 2004

Statistics of coronal heating

1. Statistics of coronal heating
    - Need for statistics
    - Statistics from observations
    - Statistics from simulations
2. Coupled shell-models for a coronal loop
    - Simple shell-model
    - Coupled shell-models
3. Results of the loop shell-model
    - Overview of fields
    - Energy, and energy dissipations
    - Statistics of dissipation events
4. Discussion

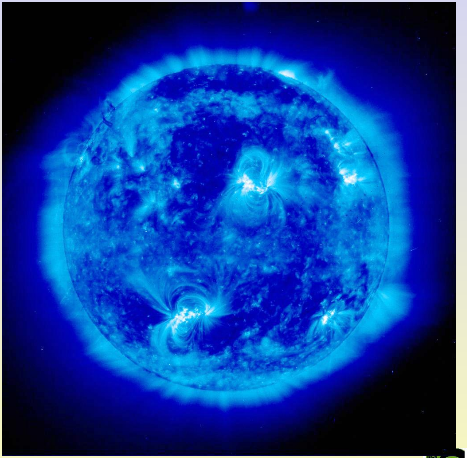
Context

Solar corona:

- very large Reynolds numbers:
  - $\Longrightarrow$ high complexity
  - $\Longrightarrow$ wide range of scales, in particular small scales, not resolved by remote sensing measurements
- the heating problem

$\Longrightarrow$ Need of *statistical studies*: observations, theory, simulations

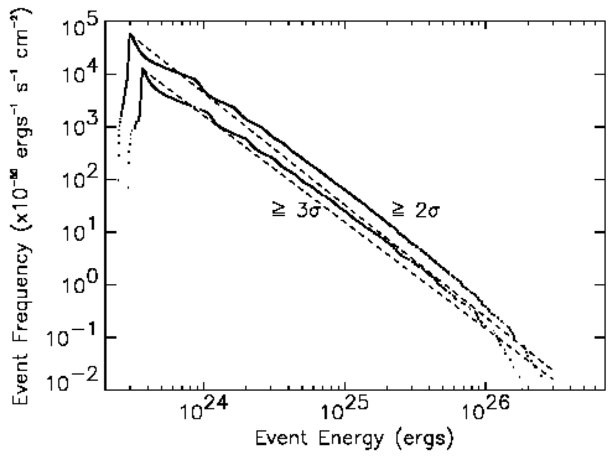
- histograms (fields, increments, events)
- correlations
- structure functions, flatness



EIT 17.1 nm, 11 Sep 1997

Statistical observations: events

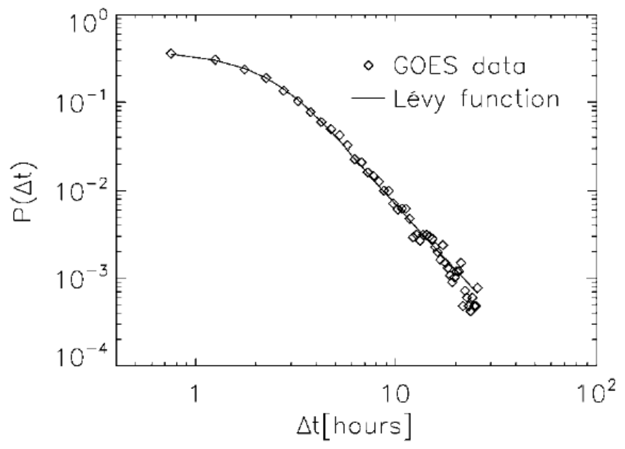
Energy in events observed by TRACE (Parnell&Jupp 2000):



Also: Aletti et al. 2000 (SOHO/EIT), Aschwanden et al. 2000...

Statistical observations: events waiting times

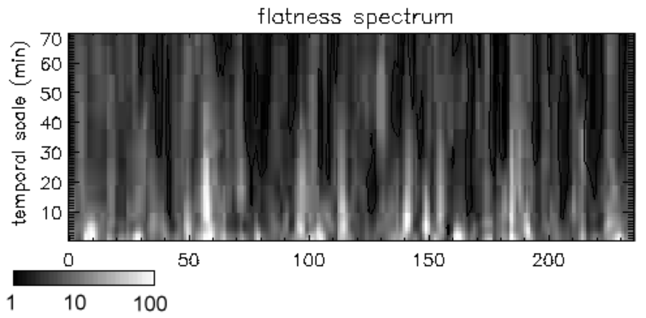
Durations between 2 consecutive events, from GOES X-ray flux (Lepreti, Carbone & Veltri 2001):



Power-law tail, *non-Poissonian process*.

Statistical observations: intermittency

Flatness spectrum of SUMER lightcurves (Patsourakos & Vial 2002):

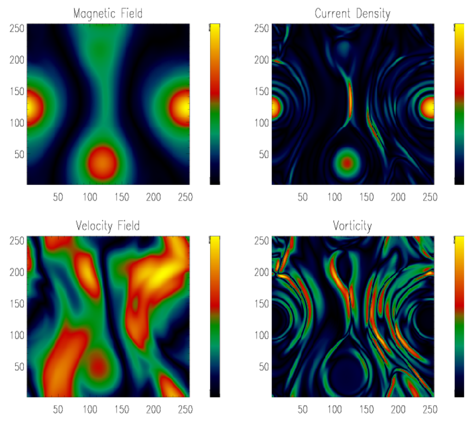


⟶ *intermittency*

Numerical simulations of MHD

Snapshot from 2D reduced MHD simulation (Georgoulis, Einaudi & Velli 1998)

⟶ first *statistics of events* from simulations

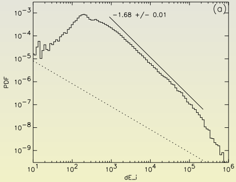


But 3D direct numerical simulations are too slow for statistics and have too small Reynolds numbers:
need *simplified* models.

Simplified 3D simulations

Cellular automata:

- Isliker et al. 1998–2000: energy input at random positions, cascade of magnetic field
- Buchlin et al. 2003: geometry of a loop, energy input at loop boundaries, cascade of current density.



Consistent with MHD, but non-linear interactions are not satisfactory (lack of intermittency)
⟶ build *new simplified models*

Coupled shell-models for a coronal loop

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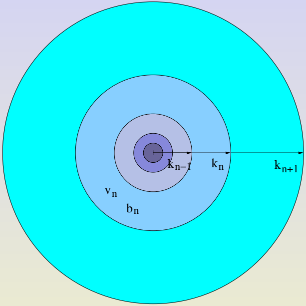
MHD shell-models

Giuliani and Carbone, 1998:

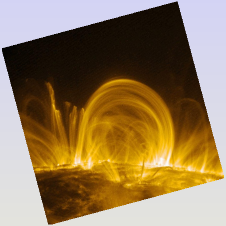
- Concentric shells in Fourier space, logarithmically spaced, very small number of modes (24)
  but *wide range* of scales, $Re > 10^6$
- Non-linear interactions between neighboring modes, conservation of *MHD invariants*



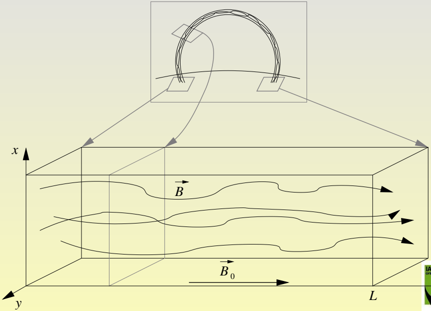
Evolution equation for Elsässer mode $Z_n^s = u_n + sb_n$ $(s = \pm)$:

$$\frac{\mathrm{d}Z_n^s}{\mathrm{d}t} = \underbrace{-k_n^2(\nu^+ Z_n^s + \nu^- Z_n^{-s})}_{\text{dissipation}} + ik_n \underbrace{T_n^{s*}(Z_{n\pm1,\pm2}^{\pm s})}_{6\text{ terms } Z_{n_1}^+ Z_{n_2}^-}$$

A loop: shell-models coupled by Alfvén waves



- MHD region (loop) with a dominant $\vec{B}_0$, with fixed geometry
- *Non-linear* dynamics in "planes" $\longrightarrow$ *done by the shell-models*
- *Alfvén waves* along $\vec{B}_0$, which couple the shell-models
- *Forcing*: a velocity field is imposed at the *photosphere*



(same setup as our CA; gives model similar to Nigro et al. PRL 2004).

Results of the loop shell-model

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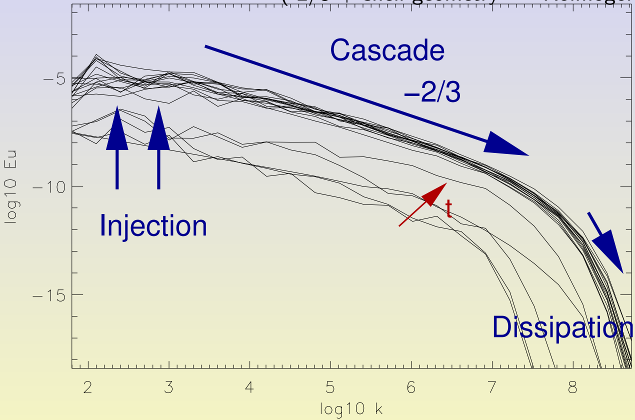
Spectrum development towards small scales

(-2/3 + shell geometry = "Kolmogorov -5/3")



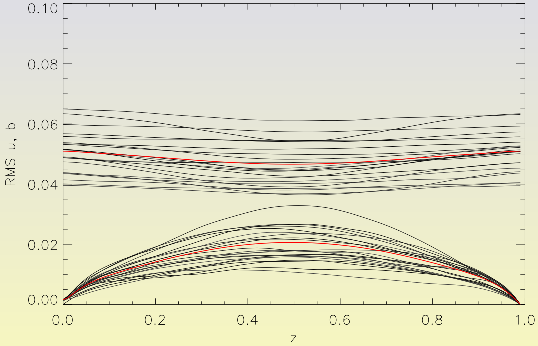
... due to the non-linear terms

as in any shell-model or MHD model

Fields along the loop

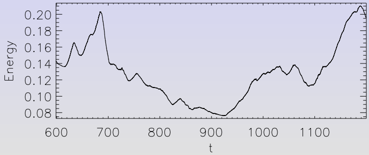
100 planes (=100 coupled shell-models)

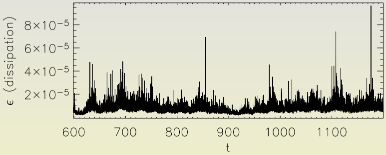
RMS velocity and magnetic field as a function of the position on the loop, for several times:



Unit of length: length of loop $L = 10\,\mathrm{Mm}$. Aspect ratio of 10.
Unit of velocity and magnetic field: Alfvén velocity $v_A = 10\,\mathrm{Mm/s}$.

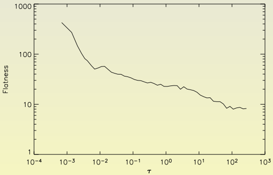
Energy and dissipation power time series





Unit of time: one crossing of the loop by the Alfvén wave

Units of energy and power: 10^{19} J and 10^{19} W for $L = 10\,\mathrm{Mm}$, $v_A = 10\,\mathrm{Mm/s}$, $\rho = 10^{-12}\,\mathrm{kg/m^3}$

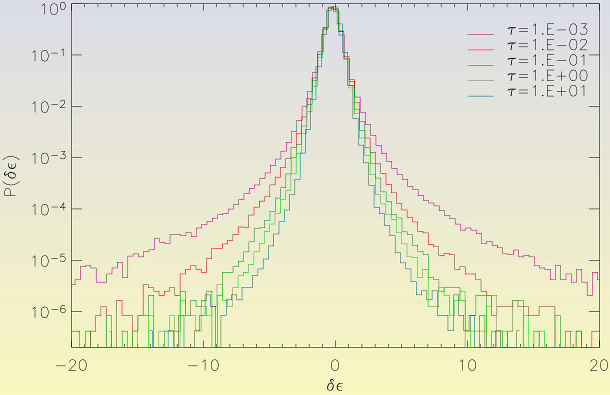


Dissipated power: high intermittency (and long-range correlations)

Data available from times 0 to 4000

Histogram of differences in dissipation time series

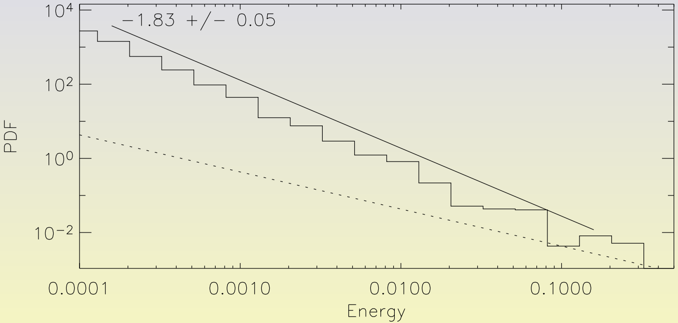
Rescaled histograms of increments
(as in Hnat et al. 2003, Sorriso-Valvo et al. ...):



No mono-scaling ⟶ intermittency

Statistics of dissipation events

Find “events” in dissipation time series
(Events defined by a threshold in the time series of dissipation power.)
and get distributions of *event energies*:



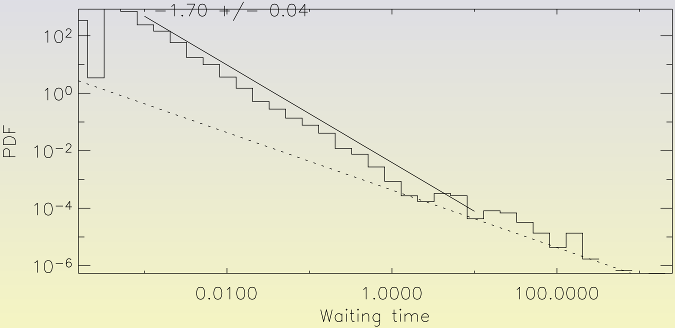
Wide power-law, similar to observations
(Aletti, Aschwanden, Parnell...)

Statistics of dissipation events

Find “events” in dissipation time series

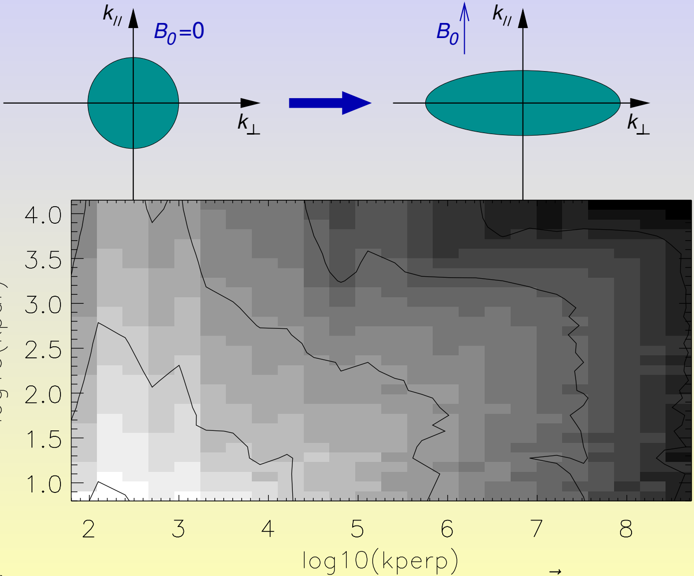
(Events defined by a threshold in the time series of dissipation power.)

and get distributions of *waiting times* beween two events:



The modellization of non-linear interactions allow this to be *not* a Poissonian process (like in Lepreti 2001).

Looking for spectrum anisotropy



$(k_\perp, k_\parallel)$ spectrum, obtained by Fourier transform along $\vec{B}_0$

Discussion

This model reconciles *two constraints*: computing speed, and good representation of the non-linear terms of MHD

Can reproduce most observational statistics, including

- waiting-time distributions
- intermittent behavior of dissipation

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Current and future work:

- Looking for statistical methods adapted to both numerical and obervational constraints
- Produce statistics of observable variables from dissipation in models (see poster $\boxed{\text{C9}}$ by Susanna Parenti)

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Current and future work:

- Looking for statistical methods adapted to both numerical and obervational constraints
- Produce statistics of observable variables from dissipation in models (see poster $\boxed{\text{C9}}$ by Susanna Parenti)
- How are particles accelerated in such models?

References

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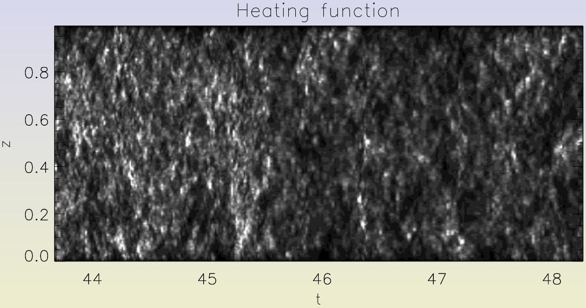
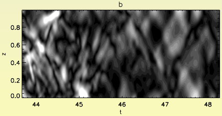
Heating function

Dissipated power as a function of time and position along $\vec{B}_0$:



Dominated by the largest $k_\perp$ modes (smallest scales):

$|B|^2$ $k_\perp = k_0 \times 2^{8}$



$|B|^2$ $k_\perp = k_0 \times 2^{18}$