Convection Processes in Astrophysics, Fusion and Laboratory plasmas

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OUTLINE

• Convection and intermittency in space plasmas

• Convection and intermittency in Laboratory Plasmas

• Convection and intermittency in Magnetic Fusion Plasmas
Definitions: Convection and Intermittency

- Convective events denote here structures with large velocities with respect to the background, therefore, the Galilean transformation, \( \mathbf{r} \rightarrow \mathbf{r} + vt \) does not hold.

- Intermittency is a term that describes phenomena with dynamics deviate from a Gaussian random process.
Large Twisting Prominence in the Sun: Events that are intermittent and Convective

The configuration of a helmet streamer and the density profile across this structure

From top to bottom: wind speed, magnetic field azimuthal angle, proton number density, density fluctuations and normalized density fluctuations, proton temperature, magnetic field magnitude, total pressure, and plasma beta, respectively
X17.0 x-ray flare in AR0810 with a 3B optical flare at S06E89, leading to a shock 43.5 hours later on 09 Sep 2005 (DOY 252) at 1310 UT.

M2.4 x-ray flare in AR0588 and a sub optical flare at S18E15
Intermittency seems to occur inside and outside the sun

O IV transition region recorded in a quiet Sun region by SUMER/SOHO. It was found that a significant proportion of points in the observed area exhibit clear indications of intermittency, irrespectively of their intrinsic intensity.

S. Patsourakos - J.-C. Vial, Astronomy & Astrophysics, 2002
Linear Plasma Devices (CSDX, PISCES)

- Langmuir probe
- RF Source
- Gas Inlet: Argon
- Transparent End-plate
- Phantom V7 camera
- Pump
Good agreement between the images profiles and fluctuations and those done using Langmuir probe for scales above 3 mm.
Inside the main plasma column

- The system transits from low to high mode number fluctuations in time and can remain in one of the modes for relatively long time.
- One can no longer speak of "stationary turbulence"...
- No evidence of zonal flows were observed in the movies.

Camera settings:
Integration time 1 μs
Time between frames 15 μs
32x32 pixels
Fast Imaging allows the observation of the growth of avaloids, their scale lengths and velocities.

No detachment of the structure, hence, it is not a “blob” but rather has a finger-like shape.

Camera setting:
Integration time 1 μs
Time between frames 15 μs
32x32 pixels

The vessel wall
From an “average movie” imaging half the main plasma column and the SOL, the convective structures properties are:

Life-time $\sim 60 \mu$s;

$L_{r, \text{avaloid}} \sim 5$ cm;

$L_{\theta, \text{avaloid}} \sim 2$ cm; $V_{r, \text{avaloid}} \sim 10^5$ cm/s

$V_{\theta, \text{main plasma}} \sim 4.5 \times 10^4$ cm/s

$V_{\theta, \text{avaloids}} \sim 4.5 \times 10^4$ cm/s
The conditionally averaged movie reveals that the onset of avaloids is associated with the non-linear evolution of the poloidal number $m=1$ instability.
Comparing Laboratory Plasma to SOHO

Linear plasma device: Plasma in the far SOL exists during and because of avaloids.

The sun: Plasma in far space exists during and because of the solar flares.

Furthermore: Because of the flat profiles and damping caused by the connection to the target plates, turbulence around the separatrix is the main cause of turbulence in the SOL.
The bursts radial velocity is far from being negligible reaching 1/10th of the sound speed. The radial scale of the bursts is about 1 cm.

**The radial scale of the bursts [mm]**

Intermittent Bursts Contribute to about 50% of the total radial transport while occupying only 20% of the total duration of the signals.

**The radial velocity of the bursts [m/s]**

AVA LOIDS are defined as large-scale concentration of density with high radial velocity encountered intermittently in the scrape-off layer.
Fusion for energy production

Numbers to keep in mind

**Abundant Energy From Sea Water**

| 60 Cups Sea Water | = | 2 Tons of Coal |
| Thimble of $^2$H ($^2$D) Deuterium | = | 20 Tons of Coal |

### Magnetic fusion

- **Reaction:** $D + T \rightarrow ^4\text{He} + n$
- **Ignition Temperature:** 13 (million °C)
- **Output Energy:** 17,680 (keV)

### Inertial fusion
Particle trajectory inside a Tokamak are said to be **CLOSED** as they return to their initial position after a number of toroidal rounds.
The Scrape-off Layer (SOL) is a region in the tokamak where the field lines are “OPEN” as they are connected to the first wall.

- The SOURCE of plasma in the SOL is mainly turbulence.

- In H-mode, plasma in the SOL is caused by turbulence and Edge Localized Modes (ELMs).

- The plasma-wall interactions lead to the first wall deterioration via sputtering. This limits the life-time of the confinement device.

- Impurities that come from the wall find its way back into the plasma core and deteriorate the confinement.
Turbulence and radial Transport in tokamaks

Turbulence in this region, around the separatrix, determines the particle confinement time in a tokamak.

Turbulence in the core can be described as “diffusive”

Turbulent transport in the SOL has two components:

1) **Diffusive Transport:**
   Small radial velocity with respect to the sound speed

2) **Convective Transport:**
   Significant radial velocity up to the order of the sound speed (1/10th)
Universality of avaloids by Comparing:
the Tore Supra, Alcator C-MOD, MAST tokamaks and the PISCES linear device

**Tore Supra tokamak**
- \( a = 76 \text{ cm}, R = 2.32 \text{ m} \)
- \( B_T = 3.5 \text{ T}, I_p = 1 \text{ MA} \)
- Limiter machine

**Alcator C-MOD tokamak**
- \( a = 21 \text{ cm}, R = 70 \text{ cm} \)
- \( B_T = 5.3 \text{ T}, I_p \sim 0.8 \text{ MA} \)
- Divertor machine

**MAST Spherical tokamak**
- \( a = 52 \text{ cm}, R = 73 \text{ cm} \)
- \( B_T = 0.6 \text{ T}, I_p = 700 \text{ kA} \)
- First wall far from the LCFS

**PISCES**
- \( n_e \sim 10^{17} \text{ m}^{-3}, T_e \sim 10 \text{ eV}, B = 0.12-0.24 \text{ T} \)
- Plasma radius \( = 2.5 \text{ cm} \)
- Vessel radius \( = 10 \text{ cm} \)
Plasma Far from the Last Closed Flux Surface in PISCES and MAST exists in form of intermittent bursts

PISCES Linear Plasma Device

MAST tokamak

![Graph showing plasma behavior](image-url)
Similarity of the PDF of $I_{\text{sat}}$ fluctuations
- Gaussian for negative fluctuations
- Strongly Skewed for positive fluctuations

Similarity of the power spectra of $I_{\text{sat}}$
- One scaling region
- Approximately the same scaling exponent -1.6
- Large scales
Similarity of the avaloid temporal signature

- Non-conservation of mass
- Asymmetric shape (like ELM’s or saw teeth)
- Imaging of avaloids on MAST using the Phantom V4 camera with 50 $\mu$s exposure time and 500 $\mu$s between frames (No correlation between two consecutive frames).
- Avaloids, as in CSDX and PISCES, are ‘observed’ to remain attached to the main plasma.
- Avaloids extend radially far from the separatrix with elongated structures.
(Recent) Progress in understanding turbulence and radial transport in the SOL of magnetic fusion devices

• Intermittency in the SOL of magnetic fusion devices is caused by large-scale structures with large radial velocities that we call avaloids.

• Avaloids result from the non-linear evolution of a low poloidal number edge instability.

• Universality: Avaloids have the same properties on different magnetic fusion devices.
An illustration of the sun structure:
1. Core
2. Radiative zone
3. Convective zone
4. Photosphere
5. Chromosphere
6. Corona
7. Sunspot
8. Granules
9. Prominence