The Tokamak as a Complex Physical System:

Introduction and Focus on L→H Transition

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WCI Symposium
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• By request, a ‘Colloquium’ type talk

• Not an OV of tokamak phenomenology, rather ➔ an introduction focused on ideas

• In the spirit of:
  “It is better to uncover one thing, than to cover everything equally.”

    - Walter Kohn
Credits

B.B. Kadomtsev

Tokamak Plasma:
A Complex Physical System
"The Garden of Earthly Delights" (1503 – 1504)
Hieronymous Bosch
Museo Del Prado, Madrid
Theme

“Tokamak plasma is a complex physical system. Various physical processes exist and interact simultaneously there. That is why the deeper the studies are, the more sophisticated are the discovered phenomena. Here, similar to many paintings by the prominent artist Hieronymous Bosch, there exist many levels of perception and understanding. At a cursory glance at the picture, you promptly grasp its idea. But under a more scrutinized study of its second and third levels, you discover a new horizon of a deeper life, and it turns out that your first impressions become rather shallow.”

- B.B. Kadomtsev
Theme, cont’d

• Thoughts on Perspective
  – complex plasma phenomenology viewed in terms of *states of self-organization* and *bifurcation transitions between them*
  – concepts for description:
    • feedback loops → how do interacting agents regulate one another?
    • structure formation from inverse cascade → how does coherent large scale order emerge from turbulence?
    • pattern selection → which of competing structural states actually emerges?
    • probabilistic formulations → how assess likelihood of states and transition?
Outline

• What is a Tokamak?

• ‘Self Organization’ ↔ How do profiles form?
  – basic idea, scales
  – a profile as a self-organized criticality (!?)

• Focus: the L→H transition
  ⇒ Layer1: transport bifurcation
  – profiles ‘morph’! ⇒ the L→H transition
  – some basic results and ideas
  – Intermezzo: flows within flow ⇒ zonal modes
  ⇒ Layer2: multi-shear interaction
Outline (cont’d)

⇒ Layer3: The challenge of prediction and control of self-organization process

⇒ Focus: L→H transition
  • Thresholds and Hysteresis
  • Uncovering ELMs
  • Controlling ELMs

⇒ Layer4: Now that we have the H-mode, do we really want it?

• Summary
What is a Tokamak?
Magnetic Fusion

What is required for ignition?

- Energy content
- Confinement

Fuel: D, T

Amount/density \( n \)

Ignition temperature \( T \)

Energy confinement time \( \tau_E \)

Fusion power \(~ n^2 T^2 (~ \beta^2 B^4) \geq \) Loss power \(~ \frac{nT}{\tau_E} \)

\[ n \cdot T \cdot \tau_E \geq 3 \times 10^{28} \text{ m}^{-3}\text{Ks} \]

Lawson criterion for D-T fusion

\( \Rightarrow \) Good confinement required for ignition!
Tokamak: a leading candidate for magnetic fusion

- Magnetic fusion devices
  - Tokamak
  - Helical device (stellerator)
  - Spherical tokamak (ST)
  - Reversed field pinch (RFP)

Comparison between magnetic fusion devices

Plasmas are confined in closed toroidal magnetic fields

![Diagram showing tokamak and helical device configurations with labels for toroidal and poloidal fields.](image)
Tokamak: a leading candidate for magnetic fusion

### PARAMETERS

<table>
<thead>
<tr>
<th></th>
<th>ITER</th>
<th>KSTAR</th>
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<tbody>
<tr>
<td>Major radius</td>
<td>6.2m</td>
<td>1.8m</td>
</tr>
<tr>
<td>Minor radius</td>
<td>2.0m</td>
<td>0.5m</td>
</tr>
<tr>
<td>Plasma volume</td>
<td>830m³</td>
<td>17.8m³</td>
</tr>
<tr>
<td>Plasma current</td>
<td>15MA</td>
<td>2.0MA</td>
</tr>
<tr>
<td>Toroidal field</td>
<td>5.3T</td>
<td>3.5T</td>
</tr>
<tr>
<td>Plasma fuel</td>
<td>H, D-T</td>
<td>H, D-D</td>
</tr>
<tr>
<td>Superconductor</td>
<td>Nb₃Sn, NbTi</td>
<td>Nb₃Sn, NbTi</td>
</tr>
</tbody>
</table>
Is Magnetic Fusion a Folly?

“The Haywain Triptych”
Hieronymous Bosch, Museo Del Prado, Madrid
Advances in Tokamak Performance

• Progress in tokamak fusion comparable to progress in computing power and particle accelerator energy.

• The next step (ITER) will be operated at high Q (≈ 10).
Major Research Topics in Fusion Science

- Turbulence & transport → Anomalous transport of energy, particle, momentum
- Macroscopic instabilities → Plasma disruption & $\beta$ limit
- Edge & boundary control → Confinement performance, impurity influx, wall damage
- Heating & CD, Particle control → Steady state operation
- Energetic particles → plasma + alpha particles
Practical Importance: Ignition and Beyond

- *Transport determines profiles and thus is critical to ignition!*

- To accurately predict plasma performance
  - Major performance parameters, such as fusion power, depend strongly on transport level i.e. $T, \tau_E$

- To achieve advanced tokamak plasma through active profile control
  - Control of pressure, current, and rotation profiles consistent with MHD stability
  - Formation and control of transport barriers for high confinement
  - Optimization of profiles for high bootstrap current fraction for steady state

PJ Knight et al., 26th EPS on Conf. on Contr. Fusion and Plasma Physics
Flow Chart

Self-Organization of Profiles

Layer 1: L→H Transition as Transport Bifurcation

Intermezzo: Zonal Modes

Layer 2: Multi-shear Interaction

Layer 3: Challenge of Prediction and Control

Layer 4: Do we really want the H-mode?
Primer on Turbulence in Tokamaks

2 scales:
\[ \rho \equiv \text{gyro-radius} \]
\[ a \equiv \text{cross-section} \]
\[ \rho^* \equiv \rho/a \rightarrow \text{key ratio} \]

- \( \nabla T, \nabla n, \) etc. driver
- Quasi-2D, elongated cells aligned with \( B_0 \)
- Characteristic scale \( \sim \) few \( \rho_i \)
- Characteristic velocity \( v_d \sim \rho^* c_s \)

- Transport scaling: \( D \sim \rho v_d \sim \rho^* D_B \sim D_{GB} \)
  - i.e. Bigger is better! \( \Rightarrow \) sets profile scale via heat balance

- Reality: \( D \sim \rho^\alpha D_B \), \( \alpha < 1 \) \( \Rightarrow \) why?
• Cells “pinned” by magnetic geometry

• Remarkable similarity

<table>
<thead>
<tr>
<th>Turbulent transport in toroidal plasmas</th>
<th>Sandpile model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Localized fluctuation (eddy)</td>
<td>Grid site (cell)</td>
</tr>
<tr>
<td><em>Local turbulence mechanism:</em></td>
<td><em>Automata rules:</em></td>
</tr>
<tr>
<td>Critical gradient for local instability</td>
<td>Critical sandpile slope ($Z_{\text{crit}}$)</td>
</tr>
<tr>
<td>Local eddy-induced transport</td>
<td>Number of grains moved if unstable ($N_f$)</td>
</tr>
<tr>
<td>Total energy/particle content</td>
<td>Total number of grains (total mass)</td>
</tr>
<tr>
<td>Heating noise/background fluctuations</td>
<td>Random rain of grains</td>
</tr>
<tr>
<td>Energy/particle flux</td>
<td>Sand flux</td>
</tr>
<tr>
<td>Mean temperature/density profiles</td>
<td>Average slope of sandpile</td>
</tr>
<tr>
<td>Transport event</td>
<td>Avalanche</td>
</tr>
<tr>
<td>Sheared electric field</td>
<td>Sheared flow (sheared wind)</td>
</tr>
</tbody>
</table>

FIG. 1. A cartoon representation of the simple cellular automata rules used to model the sandpile.
• ‘Avalanches’ form!

Extended avalanches form

• Avalanching is a likely cause of ‘gyro-Bohm breaking’

  ➔ localized cells self-organize to form transient, extended transport events

• Akin domino toppling:
• Self-Organized Profiles can be non-trivial

Note: SOC profile ≠ (linearly) marginal profile

FIG. 3. The average sandpile profiles for a marginal case and a SOC case.

Note: SOC profile ≠ (linearly) marginal profile
Flow Chart

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Layer 1: L→H Transition as Transport Bifurcation

Intermezzo: Zonal Modes

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Layer 4: Do we really want the H-mode?
What is L→H Transition

- Spontaneous transition from low to high confinement in region of edge layer
- Edge transport barrier forms: $\Delta T \sim 1\text{keV}$ in 1~2cm
- Turbulence and transport suppressed in edge transport barrier region
L→H Transition

- Key Application: Triggering the L →H Transition
  - L→H Transition
  - Transport bifurcation, ‘phase transition’ ⇒ $P_{\text{thresh}}$, hysteresis, etc.
  - Characterized by reduction of transport, turbulence in localized edge layer
  - Likely related to $V_{ExB}$ shear suppression of turbulent transport in edge layer

A. Hubbard et. al. 2002

J.W. Hughes et al., PSFC/JA-05-35
How is transport suppressed?

➔ shear decorrelation!

Back to sandpile model:

2D pile +

sheared flow of grains

Avalanche coherence destroyed by shear flow
• Implications

FIG. 12. (a) Frequency spectra with and without a shear flow region. This shows a marked decrease in the low-frequency power (with shear) and a commensurate increase in high-frequency power. (b) The insert shows the decorrelation time ($\tau_d=1/\omega$) as a function of the shear parameter (the product of the shearing rate and the size of the shear zone).

FIG. 14. The slopes of a sandpile with a shear region in the middle, including all the shear effects (diamonds) and just the transport decorrelation and the linear effect (circles).

FIG. 11. Time evolution of the overturning sites (like Fig. 4). The avalanches do not appear contiguous in time because only every 50th time step is shown. (a) The shear-free case shows avalanches of all lengths over the entire radius. (b) The case with sheared flow shows the coherent avalanches being decorrelated in the shear zone in the middle of the pile.
i.e. how generate the sheared flow?

→ First Theoretical Formulation of L→H Transition as an

- Transport Bifurcation
- \( \langle E_r \rangle \) Bifurcation

⇒ First Appearance of S-curve in a Physical Model of L→H Transition

⇒ First Formulation of Criticality Condition (Threshold) for Transport Bifurcation

→ First Theoretical Ideas on Hysteresis, ELMs, Pedestal Width, .....
→ Coupling of Transport Bifurcation to turbulence, $\langle \nu_E \rangle'$ suppression

→ Hinton '91, et. seq. (some extension to 1D)

\[ Q = -\frac{\chi_T}{1 + \alpha \nu'_E} \frac{1}{2} \nabla T - \chi_{neo} \nabla T \]

\[ \nu'_E = -\frac{\partial}{\partial r} \left( \frac{c}{eBn_0} \nabla p \right) \]

Heat flux $S$-curve induced by profile-dependent shearing feedback

Profile Bifurcation

FIG. 2. Temperature profiles near the power threshold (arbitrary units): (a) $Q(a) = 0.99 Q_c$; (b) $Q(a) = 1.01 Q_c$

FIG. 4. Power hysteresis in the energy confinement time (arbitrary units): (a) increasing power; (b) decreasing power.
Swallow’s Tail - Series on Catastrophes by Salvador Dali
→ Flux Landscape and Speed scaling for 1st order transition (P.D. et al, ’97, Lebedev, P.D., ’97)
→ motivated by ERS/NCS experiments

Cross-cuts of landscape at different positions

FIG. 2. Dependence of the flux function $\Phi$ on the value of density gradient in different radial locations.

→ Transition Front Location

$X_F \sim (D_{neot})^{1/2} \left( \frac{\Gamma - \Gamma_{crit}}{\Gamma_{crit}} \right)^{1/2}$

→ Generalized Maxwell Criterion to problem with radial structure

Constant flux and barrier transition layer
Layer I, cont’d

→ mechanism for confinement improvement and turbulence suppression:
  
→ Shear enhanced decorrelation: BDT ’90, Hahm-Burrell ’94

→ nonlinear simulations, analysis (90’s) → support trend especially for stress driven flows

→ First vs. Second order Transition (still ongoing)

→ Reynolds stress driven flow shear
  
P.D. and Kim, ’90

→ Predator - Reynolds stress driven shear
  Prey - Turbulence intensity

→ Combined 0D Predator-Prey
  with transport bifurcation
  
P.D., et.al., ’94
  Carreras, et. al., ’95
Flow Chart

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Preamble I

• Zonal FlowsUbiquitous for:
  ~ 2D fluids / plasmas with Ro < 1
  Ro < 1 ↔ Rotation $\vec{\Omega}$, Magnetization $\vec{B}_0$, Stratification
  Ex: MFE devices, giant planets, stars…
Zonal Flows

Tokamaks

planets
Heuristics of Zonal Flows a):

Simplest Possible Example: Zonally Averaged Mid-Latitude Circulation

- classic GFD example: Rossby waves + Zonal flow
  (c.f. Vallis '07, Held '01)
- Key Physics:

  ![Diagram of energy radiation and momentum convergence](image)

  **Rossby Wave:**
  \[
  \omega_k = -\frac{\beta k_x}{k^2} \\
  v_{gy} = 2\beta \frac{k_x k_y}{k^2} \\
  \langle \tilde{v}_y \tilde{v}_x \rangle = \sum_k -k_x k_y |\hat{\phi}_k|^2 \\
  \therefore v_{gy} v_{phy} < 0 \\
  \rightarrow \text{Backward wave!}
  \]

  \[\Rightarrow \text{Momentum convergence at stirring location} \]
...“the central result that a rapidly rotating flow, when stirred in a localized region, will converge angular momentum into this region.” (I. Held, '01)

- Outgoing waves $\Rightarrow$ incoming wave momentum flux

![Diagram showing the flow direction and viscous damping]

- Local Flow Direction (northern hemisphere):
  - eastward in source region
  - westward in sink region
  - set by $\beta > 0$
  - Some similarity to spinodal decomposition phenomena...
• What is a Zonal Flow?
  – $n = 0$ potential mode; $m = 0$ (ZFZF), with possible sideband (GAM)
  – toroidally, poloidally symmetric $E \times B$ shear flow

• Why are Z.F.’s important?
  – Zonal flows are secondary (nonlinearly driven):
    • modes of minimal inertia (Hasegawa et. al.; Sagdeev, et. al. ‘78)
    • modes of minimal damping (Rosenbluth, Hinton ‘98)
    • drive zero transport ($n = 0$)
  – natural predators to feed off and retain energy released by gradient-driven microturbulence
Shearing I

• Coherent shearing: (Kelvin, G.I. Taylor, Dupree’66, BDT’90)
  – radial scattering + $\langle V_E \rangle'$ → hybrid decorrelation
  – $k_r^2 D_\perp \rightarrow (k_\theta^2 \langle V_E \rangle'^2 D_\perp / 3)^{1/3} = 1 / \tau_c$
  – shaping, flux compression: Hahm, Burrell ’94

• Other shearing effects (linear):
  – spatial resonance dispersion: $\omega - k_\parallel v_\parallel \Rightarrow \omega - k_\parallel v_\parallel - k_\theta \langle V_E \rangle' (r - r_0)$
  – differential response rotation → especially for kinetic curvature effects

→ N.B. Caveat: Modes can adjust to weaken effect of external shear
  (Carreras, et. al. ‘92; Scott ‘92)
Shearing II

- Zonal Shears: Wave kinetics (Zakharov et. al.; P.D. et. al. ‘98, et. seq.)
  - Coherent interaction approach (L. Chen et. al.)

\[ \frac{dk_r}{dt} = -\partial(\omega + k_0 V_E) / \partial r ; \quad V_E = \langle V_E \rangle + \tilde{V}_E \]

Mean shearing

\[ k_r = k_r^{(0)} - k_0 V'_E \tau \]

Zonal

\[ \langle \delta k_r^2 \rangle = D_k \tau \]

Random shearing

\[ D_k = \sum_q k_0^2 \left| \tilde{V}_{E,q} \right|^2 \tau_{k,q} \]

- Wave ray chaos (not shear RPA)
  - Underlies \( D_k \rightarrow \) induced diffusion

- Induces wave packet dispersion

- Applicable to ZFs and GAMs

\[ \frac{\partial N}{\partial t} + (\bar{V}_g + \bar{V}) \cdot \nabla N - \frac{\partial}{\partial r} (\omega + k_0 V_E) \cdot \frac{\partial N}{\partial k} = \gamma_k N - C\{N\} \]

\[ \Rightarrow \frac{\partial}{\partial t} \langle N \rangle - \frac{\partial}{\partial k_r} D_k \frac{\partial}{\partial k_r} \langle N \rangle = \gamma_k \langle N \rangle - \langle C\{N\} \rangle \]
Shearing III

- Energetics: Books Balance for Reynolds Stress-Driven Flows!

- Fluctuation Energy Evolution – Z.F. shearing

\[ \int d\vec{k} \omega \left( \frac{\partial}{\partial t} \langle N \rangle - \frac{\partial}{\partial k_r} D_k \frac{\partial}{\partial k_r} \langle N \rangle \right) \Rightarrow \frac{\partial}{\partial t} \langle \varepsilon \rangle = -\int d\vec{k} V_{gr}(\vec{k}) D_k \frac{\partial}{\partial k_r} \langle N \rangle \]

\[ V_{gr} = \frac{-2k_r k_\theta V_s \rho_s^2}{(1 + k_\perp \rho_s^2)^2} \]

Point: For \( d\langle \Omega \rangle / dk_r < 0 \), Z.F. shearing damps wave energy \( \langle N \rangle \sim \langle \Omega \rangle \)

- Fate of the Energy: Reynolds work on Zonal Flow

Modulational Instability

\[ \partial_t \delta V_\theta + \partial \left( \delta \langle \vec{V}_r \vec{V}_\theta \rangle \right) / \partial r = -\gamma \delta V_\theta \]

\[ \delta \langle \vec{V}_r \vec{V}_\theta \rangle \sim \frac{k_r k_\theta \delta \Omega}{(1 + k_\perp \rho_s^2)^2} \]

N.B.: Wave decorrelation essential:
Equivalent to PV transport
(c.f. Gurcan et. al. 2010)

- Bottom Line:
  - Z.F. growth due to shearing of waves
  - “Reynolds work” and “flow shearing” as relabeling → books balance
  - Z.F. damping emerges as critical; MNR ‘97
Feedback Loops I

• Closing the loop of shearing and Reynolds work

• Spectral ‘Predator-Prey’ equations

Prey → Drift waves, $<N>$

$$\frac{\partial}{\partial t} <N> - \frac{\partial}{\partial k_r} D_k \frac{\partial}{\partial k_r} <N> = \gamma_k <N> - \frac{\Delta \omega_k}{N_0} <N>^2$$

Predator → Zonal flow, $|\phi_q|^2$

$$\frac{\partial}{\partial t} |\phi_q|^2 = \Gamma_q \left[ \frac{\partial <N>}{\partial k_r} \right] |\phi_q|^2 - \gamma_d |\phi_q|^2 - \gamma_{NL} [ |\phi_q|^2 ] |\phi_q|^2$$
Feedback Loops II

• Recovering the ‘dual cascade’:
  
  – Prey → \( <N> \sim <\Omega> \Rightarrow \text{induced diffusion to high } k_r \Rightarrow \text{forward potential enstrophy cascade; PV transport} \)
  
  – Predator → \( |\phi_q|^2 \sim \langle V^2_{E,\theta}\rangle \Rightarrow \text{growth of } n=0, m=0 \text{ Z.F. by turbulent Reynolds work} \Rightarrow \text{inverse energy cascade} \)

• Mean Field Predator-Prey Model

  (P.D. et. al. ’94, DI\(^2\)H ’05)

  \[
  \frac{\partial}{\partial t} N = \gamma N - \alpha V^2 N - \Delta \omega N^2 \\
  \frac{\partial}{\partial t} V^2 = \alpha N V^2 - \gamma_d V^2 - \gamma_{NL} (V^2)V^2
  \]

System States

<table>
<thead>
<tr>
<th>State</th>
<th>No flow</th>
<th>Flow ((\alpha_2 = 0))</th>
<th>Flow ((\alpha_2 \neq 0))</th>
</tr>
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<tbody>
<tr>
<td>(N) (drift wave turbulence level)</td>
<td>(\frac{\gamma N}{\Delta \omega})</td>
<td>(\gamma_d \frac{\alpha}{\alpha})</td>
<td>(\gamma_d + \alpha_2 \gamma \frac{\alpha}{\alpha})</td>
</tr>
<tr>
<td>(V^2) (mean square flow)</td>
<td>0</td>
<td>(\frac{\gamma V^2}{\alpha} - \frac{\Delta \omega \gamma}{\alpha^2})</td>
<td>(\gamma V^2 - \Delta \omega \gamma \frac{\alpha}{\alpha^2})</td>
</tr>
<tr>
<td>Drive/excitation mechanism</td>
<td>Linear growth</td>
<td>Linear growth</td>
<td>Linear growth</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Nonlinear damping of flow</td>
</tr>
<tr>
<td>Regulation/inhibition mechanism</td>
<td>Self-interaction of turbulence</td>
<td>Random shearing, self-interaction</td>
<td>Random shearing, self-interaction</td>
</tr>
<tr>
<td>Branching ratio (\frac{V^2}{N})</td>
<td>0</td>
<td>(\gamma - \Delta \omega \gamma \frac{\alpha}{\alpha^2})</td>
<td>(\gamma_d + \alpha_2 \gamma \frac{\alpha}{\alpha})</td>
</tr>
<tr>
<td>Threshold (without noise)</td>
<td>(\gamma &gt; 0)</td>
<td>(\gamma &gt; \Delta \omega \gamma\frac{\alpha}{\alpha^2})</td>
<td>(\gamma &gt; \Delta \omega \gamma\frac{\alpha}{\alpha^2})</td>
</tr>
</tbody>
</table>
Feedback Loops III

- Early simple simulations confirmed several aspects of modulational predator-prey dynamics
  
  (L. Charlton et. al. '94)

\[
\frac{\tilde{n}}{n_0} \quad \langle V' \rangle \quad \langle V'' \rangle
\]

Shear flow grows above critical point

\[
\langle (\tilde{n} / n_0)^2 \rangle
\]

\[
\hat{\mu} / \Omega_i
\]

'With Flow' and 'No Flow'.
Scalings of \( \langle (\tilde{n} / n_0)^2 \rangle \) appear. Role of damping evident

\[
\frac{r}{a}
\]

\[
\theta
\]

Generic picture of fluctuation scale reduction with flow shear
Feedback Loops IV

• Zonal Flows Observed in Toroidal Systems
  – Fujisawa, et. al. 2004: Correlated HIBP Scattering

![Experimental Setup Diagram]

- Radial Structure
- Radial coherence C(r1,r2)

- Coherence PSD
- Potential Difference PSD

- Red – PSD of difference
- Blue - coherence

- Potential Difference PSD

- Experimental Setup

- Poloidal Cross section 1

- Poloidal Cross section 2

- HIBP#1 observation points

- HIBP#2 observation points

- ExB flow

- P~f^-0.6
**Forefront Topic**

With G. Dif-Pradalier et. al.

**Analogy with geophysics: the ‘**$\mathbf{E} \times \mathbf{B}$** staircase’**

- Quasi-regular pattern of shear layer and profile corrugations

\[ Q = -n\chi(r)\nabla T \Rightarrow Q = -\int \kappa(r', r)\nabla T(r') \, dr' \]

- ‘$\mathbf{E} \times \mathbf{B}$ staircase’ width $\equiv$ kernel width $\Delta$

- Coherent, persistent, jet-like pattern
  $\Rightarrow$ the ‘$\mathbf{E} \times \mathbf{B}$ staircase’

- Staircase NOT related to low order rationals!

Dif-Pradalier, P.D. et. al., Phys Rev E. 2010
The point:

- fit: \( Q = -\int dr' \kappa(r, r') \nabla T(r') \) \( \kappa(r, r') \sim \frac{S^2}{(r - r')^2 + \Delta^2} \) \( \rightarrow \) some range in exponent

- \( \Delta >> \Delta_c \) i.e. \( \Delta \sim \) Avalanche scale >> \( \Delta_c \sim \) correlation scale

- Staircase ‘steps’ separated by \( \Delta \)! \( \rightarrow \) stochastic avalanches produce quasi-regular flow pattern!?

N.B.

- The notion of a staircase is not new – especially in systems with natural periodicity (i.e. NL wave breaking…)
- What IS new is the connection to stochastic avalanches, independent of geometry

- What is process of self-organization linking avalanche scale to zonal pattern step?
  - i.e. How extend predator-prey feedback model to encompass both avalanche and zonal flow staircase?
  - \( \rightarrow \) spatial, domain decomposition, ala’ spinodal decomposition?
Flow Chart

Self-Organization of Profiles
Layer 1: L→H Transition as Transport Bifurcation
Intermezzo: Zonal Modes

Layer 2: Multi-shear Interaction
Layer 3: Challenge of Prediction and Control
Layer 4: Do we really want the H-mode?
Multi-Scale Flow and Feedback

- Awareness of zonal flow importance begged the question of ZF role in transition
- Realization: Since zonal flow is fluctuation driven, ZF can trigger transition but cannot sustain it.
- Transition is intrinsically a 2 predator + 1 prey problem
- Mean shear impacts Reynolds correlation as well as intensities.
Feedback Loops

- \( \nabla P \) coupling
  \[
  \partial_t \varepsilon = \varepsilon N - a_1 \varepsilon^2 - a_2 V^2 \varepsilon - a_3 V_{ZF}^2 \varepsilon
  \]
  \[
  \partial_t V_{ZF}^2 = b_1 \frac{\varepsilon V_{ZF}^2}{1 + b_2 V^2} - b_3 V_{ZF}^2
  \]
  \[
  \partial_t N = -c_1 \varepsilon N - c_2 N + Q
  \]

\( \varepsilon \equiv \) DW energy

\( V_{ZF} \equiv \) ZF shear

\( N \equiv \nabla \langle P \rangle \equiv \) pressure gradient

\( V = dN^2 \) (radial force balance)

- Simplest example of 2 predator + 1 prey problem (E. Kim, P.D., 2003)
  - i.e. prey sustains predators
  - predators limit prey
  - usual feedback

now:

- 2 predators (ZF, \( \nabla \langle P \rangle \)) compete
- \( \nabla \langle P \rangle \) as both drive and predator

- Relevance: LH transition, ITB
  - Builds on insights from Itoh’s, Hinton
  - ZF \( \Rightarrow \) triggers
  - \( \nabla \langle P \rangle \) \( \Rightarrow \) ‘locking in’

Multiple predators are possible
L→H Transition, cont’d

- Observations:
  - ZF’s trigger transition, $\nabla \langle P \rangle$ and $\langle V_E \rangle$ lock it in
  - Period of dithering, pulsations during ZF, $\nabla \langle P \rangle$ oscillation as $Q \uparrow$
    $\Rightarrow$ “I-phase”
  - Phase between $\mathcal{E}$, $V_{ZF}^2$, $\nabla \langle P \rangle$ varies as $Q$ increases
  - $\nabla \langle P \rangle \leftrightarrow$ ZF interaction $\Rightarrow$ effect on wave form

Solid - $\mathcal{E}$

Dotted - $V_{ZF}^2$

Dashed - $\nabla \langle P \rangle$
L→H Transition, again

- LCO / Intermediate Phase Now Observed in Many Experiments (L. Schmitz, et. al. 2012)

- Zonal shearing LCO during I-phase allows $\langle V_E \rangle$ to grow

- At transition, turbulence and ZF decay, mean shear locks in H-mode
L→H Transition

- Spatio-Temporal Evolution: 5-field, $k$-$\varepsilon$ Type Model
  
  (with K. Miki)
Reduced Model Captures Many Features of L → I → H Transition

Slow Power Ramp Indicates L → I → H Evolution

- Turbulence intensity peaks just prior to transition.
- Mean shear (i.e., profiles) also oscillates in I-phase.
L→H Transition

• Is the zonal flow the ‘trigger’ of the L→H transition?

• Model

Increasing ZF damping can delay or suppress transition

• Experiment – EAST (P. Manz, et. al. 2012)

\[ \frac{P_\perp}{\langle \tilde{V}^2 \rangle} \]

\[ D_\alpha \]

turbulence intensity

normalized energy transfer
L→H Transition

• Partial Conclusions
  – Dynamics of L→H transition effectively captured by multi-shear predator-prey model
  – Theory and experiment both strongly suggest that zonal flow is the trigger of L → H transition
  – Remaining Issue:
    • Connection of $P_{\text{thresh}}$ scalings to micro-dynamics, i.e. Zonal flow damping should enter $P_{\text{thresh}}$
Flow Chart

Self-Organization of Profiles

Layer 1 : L→H Transition as Transport Bifurcation

Intermezzo: Zonal Modes

Layer 2 : Multi-shear Interaction

Layer 3 : Challenge of Prediction and Control

Layer 4 : Do we really want the H-mode?
Problem in H-mode Physics: A Selected List

• What sets $P_{th}(n)$?

  Strength of hysteresis?

  – $P_{th}(n)$ scaling at high density due zonal flow collisional damping
  – Understanding of low-$n$ branch remains elusive $\rightarrow$ electron-ion coupling for low-$n$ ECH

• Little understanding of $\frac{P_{LH}}{P_{HLL}} > 1$ trends, even empirically
**ELMs (Edge Localized Modes)**

- ELMs are quasi-periodic edge relaxation bursts observed in H-mode and $\nabla P$ steepens and turbulence suppressed.
- ELMs are (likely) related to localized macroscopic MHD instabilities, possible only in states of good confinement.
- ELMs produce unacceptably LARGE transient heat load on plasma facing materials.
How control ELMs?

- RMP (cost >> $MB)  (RMP pioneered at GA, San Diego by Todd Evans)
- Small pellets, SMBI (cost $10 K)  (SMBI pioneered and developed at SWIP, Chengdu by Weiwen Xiao, L. Yao)
- Seeks to prevent formation of large transport events by perturbing $\nabla n, \nabla P$ in pedestal by injection
- How does SMBI work?  (see also T. Rhee, this meeting)
Flow Chart

Self-Organization of Profiles
Layer 1 : L→H Transition as Transport Bifurcation
Intermezzo: Zonal Modes
Layer 2 : Multi-shear Interaction
Layer 3 : Challenge of Prediction and Control
Layer 4 : Do we really want the H-mode?
Is the H-mode really THE desirable mode of operation?

(see also M. Kikuchi, this meeting)

i.e.

• ELM control

• ITER W divertor
  – High Z impurity accumulation
  – Need ELMs to avoid radiative collapse
  – But plasma facing loads?

• SOL power e-folding length (R. Goldston, et. al.)

• ECH-driven intrinsic rotation and RWM control?

...       ...

Open questions, and alternatives exist but not well explored...
Summary
What Lessons have we learned?

- Fusion plasma dynamics is rich in problems in complexity, nonlinear dynamics, self-organization, multi-scale phenomena

- The quest to understand the L→H transition has triggered much of the progress in fusion physics during past 30 years

- Much progress, but open questions remain
⇒ Outlook of the Past:

“What is the optimal configuration within which to contain the plasma?”

⇒ Outlook of the Future:

“What is the optimal means by which to achieve the self-organized state of the plasma?”