

Heat Load Broadening and Turbulence Spreading: Some Issues and a Look Ahead

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Background: The SOL Width Problem

- Long history, Key: Open field lines
- H-mode → HD Model (Goldston +)

$$\lambda_q \sim \varepsilon \rho_{\theta i} - \text{pathetically small, unfavorable } B_{\theta} \text{ scaling}$$

- Why? → ExB shear quenches SOL modes

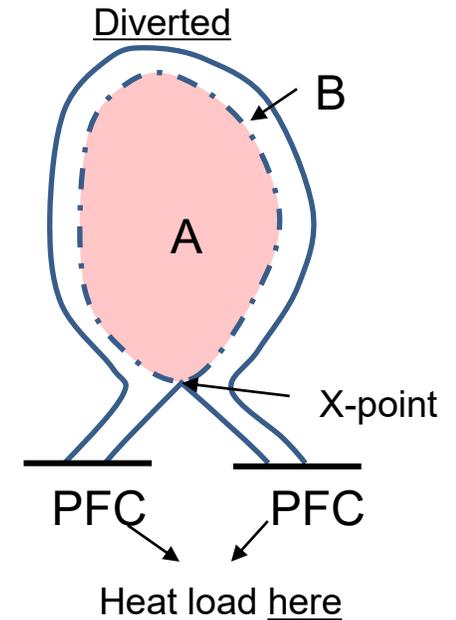
- Calculate SOL width for turbulent pedestal but locally stable SOL

– Penetration depth of turbulence spreading ?!

– See Chu, PD, Guo '22 NF

- N.B.: Many results from simulation now available, beyond color pictures

See Nami Li, Zeyu Li, this meeting



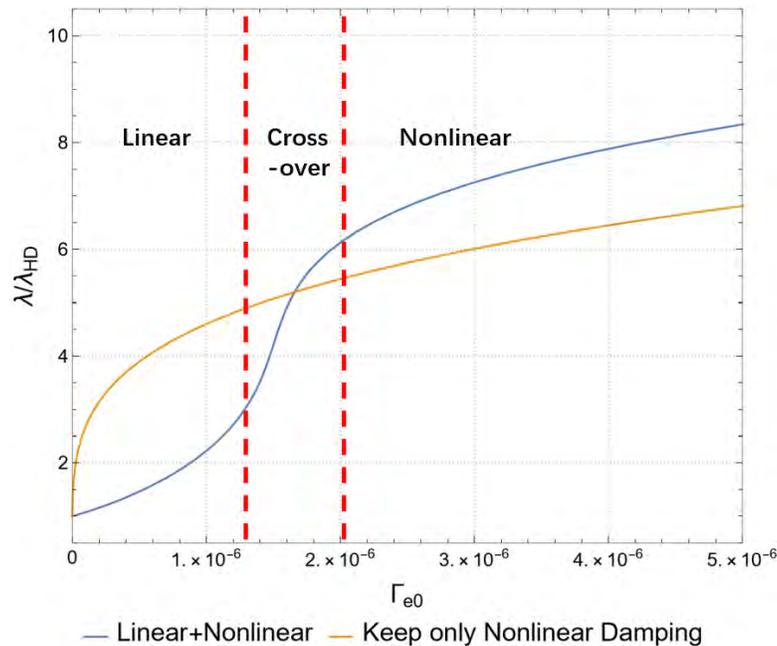
A – confined plasma
B – SOL
Dashed – separatrix

Summary: Chu, P.D., Guo '22 NF

- Turbulent scattering broadens stable SOL

$$\lambda = (\lambda_{HD}^2 + \varepsilon \tau_{\parallel}^2)^{1/2} \quad \varepsilon \approx \text{Turbulence energy intensity, in SOL}$$

- Separatrix turbulence energy flux specifies SOL turbulence drive



Spreading Calculation for ε :

$$\Gamma_{0,e} = \lambda_e |\gamma| \varepsilon + \lambda_e \sigma \varepsilon^{1+\kappa}, \quad \left[\begin{array}{l} \text{Relates } \varepsilon \text{ to} \\ \text{influx from pedestal} \end{array} \right.$$

Broadening increases with $\Gamma_{0,e}$

Non-trivial dependence

- $\Gamma_{0,e}$ must overcome shear layer barrier

Summary: cont'd

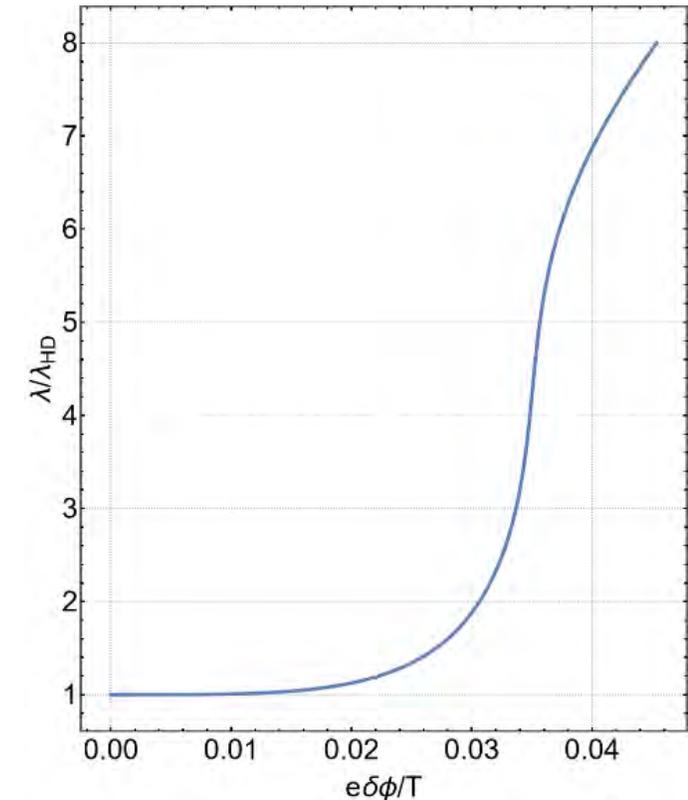
– Critical: The Cost-Benefit Question

➔ Can sufficient SOL broadening be achieved for tolerable pedestal Turbulence levels?

➔ Require λ/λ_{HD} vs. *Pedestal* fluctuation level

↔ Spreading through Shear Layer.

Interesting levels of λ/λ_{HD} for modest pedestal fluctuation $e\tilde{\phi}/T$



Fundamental Physics of Turbulence Spreading

- **Structure of the intensity flux-gradient relation ?**
- **Experiments: Ancient and Modern**
- **Pulsation Model of Spreading (New)**

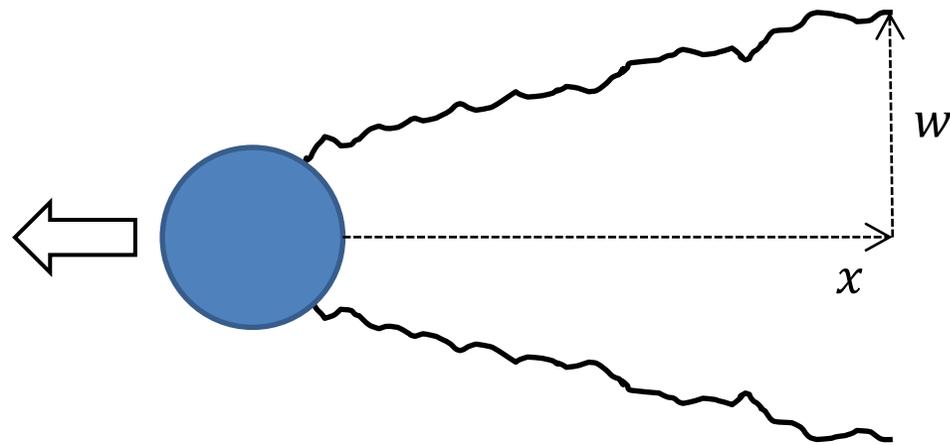
Review:

Hahm, P.D.
J. Kor. Phys. Soc.
2018

- Comment:
- Turbulence spreading is seen as a 'Deus ex Machina'
 - Fundamental Physics poorly understood

On Spreading: A Familiar Phenomenon

- Turbulence spreading underpins turbulent wake \rightarrow central example in high Re fluids



Mixing length model

Similarity theory

Spreading \longleftrightarrow

Wake expansion

cf: Landau & Lifshitz

$$w \sim (F_d / \rho U^2)^{1/3} x^{1/3}$$

$$F_d \sim \rho U^2 S C_D;$$

$$C_D \rightarrow \text{indep } \nu$$

- Spreading fundamental to $k - \varepsilon$ type models, as ε evolved as unresolved energy field \rightarrow subgrid models

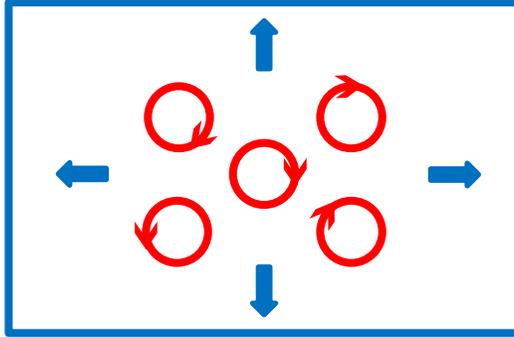
cf: Hahm, P.D. +
2004
et seq.

$$\frac{\partial \varepsilon}{\partial t} + \nabla \cdot (\tilde{V} \varepsilon) + \dots = 0$$

How render tractable ?

Illustration:

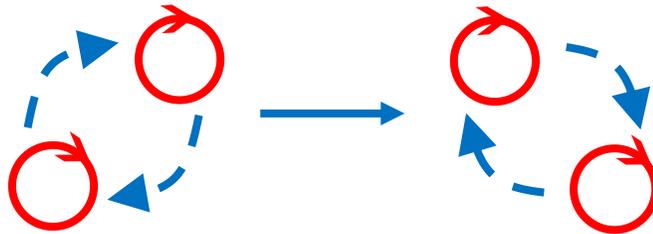
- 2D Fluid Patch
How will spread?



contrast:
k-space →
dual cascade
etc.

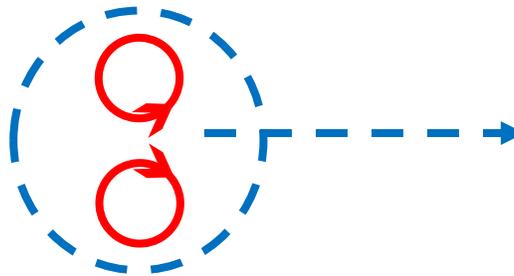
→ Random walk vortices, under mutual induction?

- but:



rotate?!

vs. Dipole pair
good for spreading



V_{pair}

- Patch expansion is poorly understood.....

On Spreading: cont'd

- What you get (usually):

$$\partial_t \varepsilon + \underbrace{\vec{V}_D \cdot \nabla \varepsilon}_{\text{drift}} + \underbrace{\langle \vec{V}_E(r) \rangle \cdot \nabla \varepsilon}_{\text{shear}} - \partial_r \underbrace{D(\varepsilon)}_{\text{turbulent mixing via closure}} \partial_r \varepsilon = P(\varepsilon) - P_{\text{damp}}(\varepsilon) \rightarrow \gamma(\vec{x}) \varepsilon$$

$\gamma = \gamma(\text{gradients, etc})$

$D(\varepsilon) \approx D_0 \varepsilon$, et. seq. \rightarrow nonlinear diffusion

\rightarrow ε evolution as nonlinear Reaction-Diffusion Problem!

(P.D., Garbet, Hahm, Gurcan, Sarazin, Singh, Naulin...)

- Used also in:
 - Multi-scale style layering models (Ashourvan +)
 - 1D L \rightarrow H models (Miki +)

On Spreading: cont'd

- Spreading as Front → Fast Propagation

i.e. $V_f \sim (\gamma D)^{1/2}$, etc i.e. Fisher

- Key component:

$$\nabla \cdot \langle \vec{V} \varepsilon \rangle \rightarrow -\nabla \cdot D(\varepsilon) \cdot \nabla \varepsilon \quad [\text{Fickian Model}]$$

Expectation: $D(\varepsilon) \sim \chi, D_n$ etc. for electrostatic turbulence

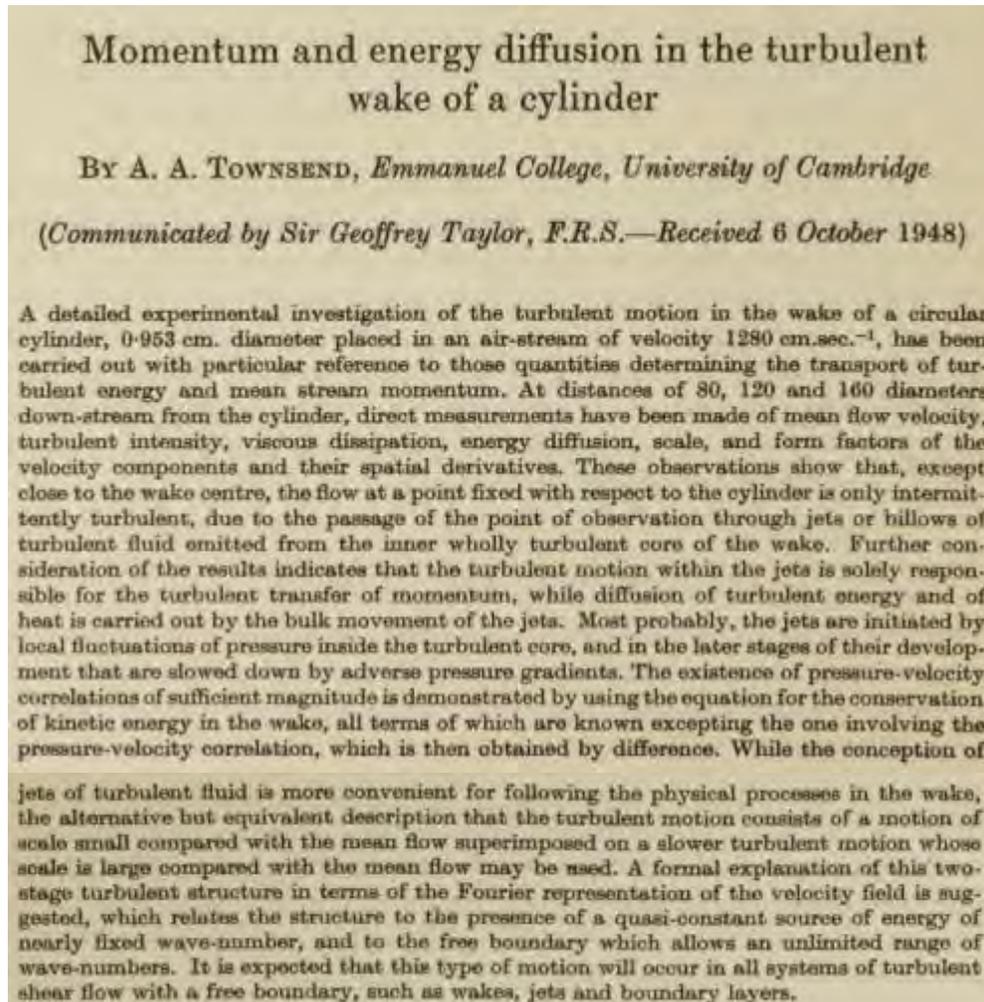
- Copious simulations: Z. Lin, W.X. Wang, S. Yi, Jae-Min Kwon, Y. Sarazin, ...

→ Observations of front tracking but critical analysis of model absent

No test of Fickian flux-gradient model

Experiments: Ancient

- Not exactly a new idea ... See Townsend '49 and book



→ Wake flow intermittently turbulent

→ Compare transport of momentum and energy (spreading)

Experiments: Ancient, cont'd

The product uv may be regarded as the rate of transport of momentum (per unit mass), and similarly the rate of transport of turbulent energy is

$$\frac{1}{2}(\overline{u^2v} + \overline{v^3} + \overline{vw^2}),$$

and, in principle, it is possible to calculate an energy diffusion coefficient δ , analogous with ϵ , by use of the defining equation

$$\overline{u^2v} + \overline{v^3} + \overline{vw^2} = -\delta \frac{\partial}{\partial y} (\overline{u^2} + \overline{v^2} + \overline{w^2}).$$

When this is attempted (figure 5), no simple behaviour is found either for δ , or for the corresponding mixing length. Negative values occur near the wake centre, and, even where the turbulence gradient is fairly uniform, δ remains large compared with ϵ ,

and decreases rapidly with distance from the wake centre. It must be concluded that the use of a diffusion coefficient to describe the transport of turbulent energy is not justified, and that energy diffusion is a process independent of momentum diffusion.

To remove this difficulty, it is not sufficient to consider the effects of intermittency. If the intermittency factor is known, then the mean intensity in the turbulent regions is

$$I_j = \frac{\overline{u^2} + \overline{v^2} + \overline{w^2}}{\gamma},$$

and I_j is found to vary only slightly over the greater part of the wake (figure 6). So a considerable transport of energy is found in the almost complete absence of a real intensity gradient, and it is difficult to see how energy flow can take place by turbulent

movements inside the jets. For the transport mechanism, there is only left the bulk movement of the jets, which is naturally outwards and away from the wake centre. The compensating inflow will consist of non-turbulent fluid transporting no turbulent energy. Consequently, the flow of energy is not dependent on the local intensity gradient (if any), but only on the mean jet velocity and the jet turbulent intensity, which in turn are determined by conditions in the turbulent core.

→ Fickian model for turbulent energy transport



→ “It must be concluded that the use of a diffusion coefficient to describe the transport of turbulent energy is not justified and that energy diffusion is a process independent of momentum diffusion”

i.e. the usual model of spreading is crap.....

→ Wake consists of ‘jets’ of turbulence energy

Experiments: Modern (c.f. Ting Long) 1

- HL-2A
- Aims:
 - Exploration of intensity flux – intensity gradient relation in edge turbulence (exploits spreading, shear layer collapse and density limit studies Long + NF'21)

- Physics of “Jet Velocity” profile

$$V_I = \langle \tilde{V}_r \tilde{n}^2 \rangle / \langle \tilde{n}^2 \rangle$$

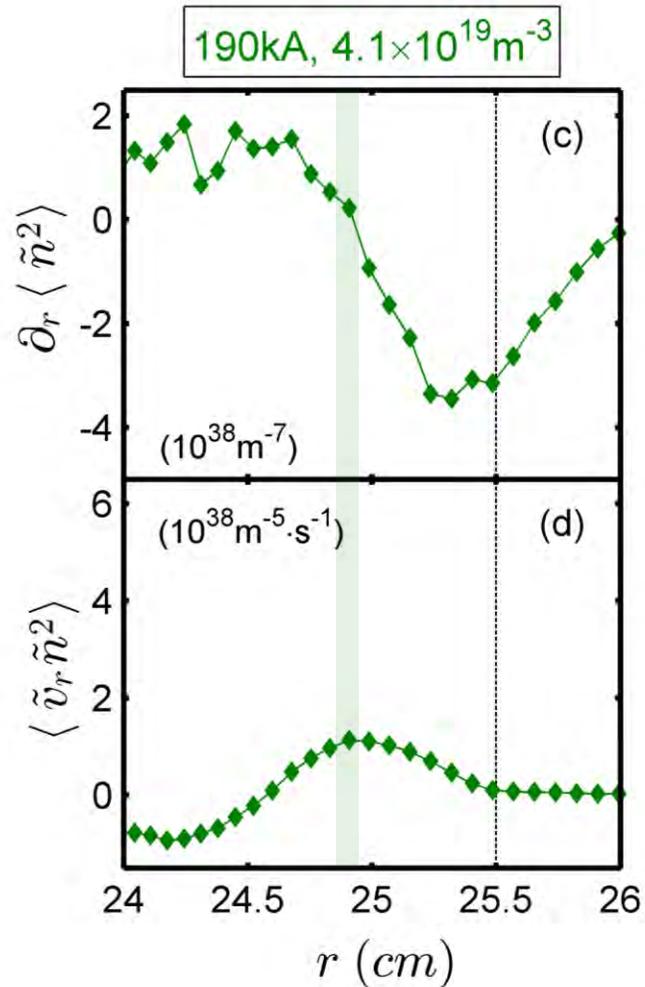
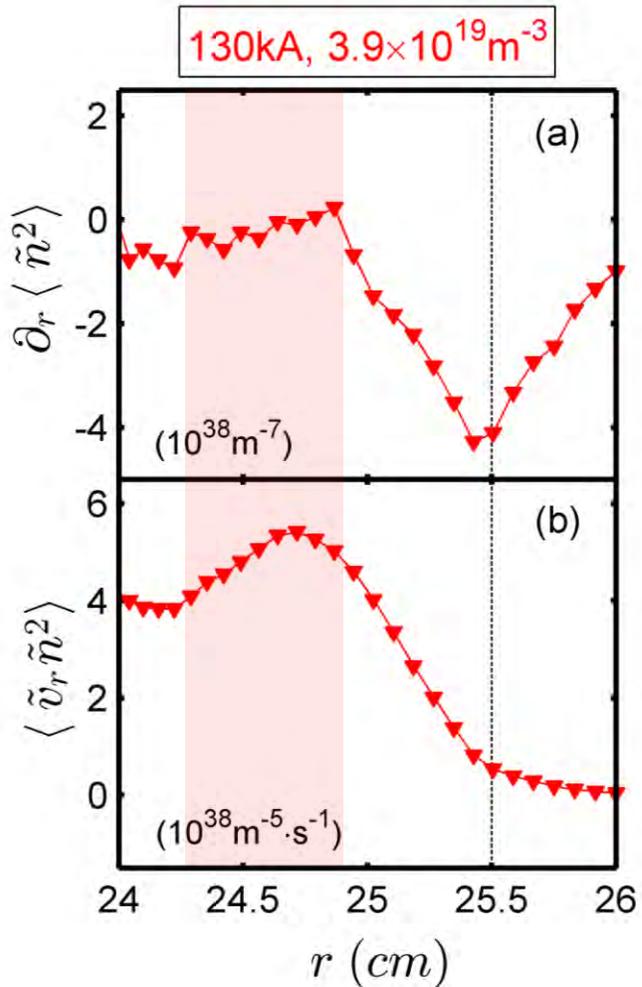
$\langle \tilde{v}_r \tilde{n}^2 \rangle \rightarrow$
spreading
flux element

N.B. Identified by Townsend

See Manz+2015 for spreading \leftrightarrow blob connection.

Experiments: Modern 2

- There exists a region in plasma edge, where the turbulence spreading flux $\langle \tilde{v}_r \tilde{n}^2 \rangle / 2$ is **large**, but the turbulence intensity gradient $\partial_r \langle \tilde{n}^2 \rangle$ is **near zero**



For close \bar{n}_e

- Lower current, width of region is $\sim 5 \text{ mm}$ ($l_{cr} \sim 4.5 \text{ mm}$)
- Higher current, width of region is $< 1 \text{ mm}$ ($\rho_i \sim 0.25 \text{ mm}$)

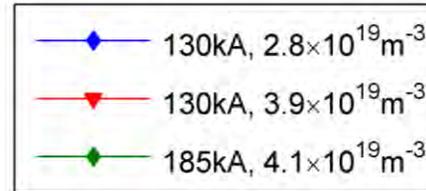
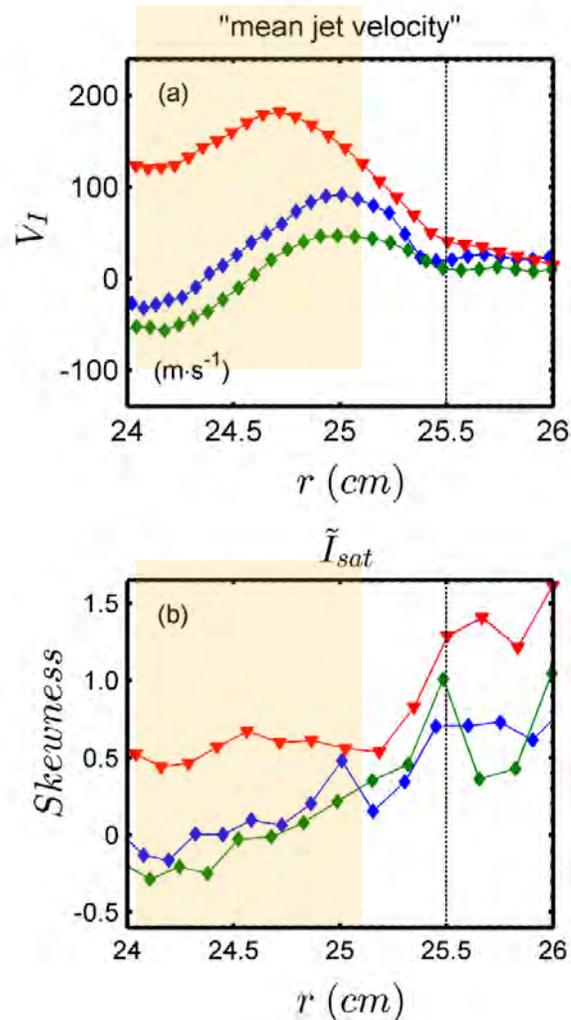
- Notice: spreading diffusivity

$$\chi_I = - \frac{\langle \tilde{v}_r \tilde{n}^2 \rangle}{\partial_r \langle \tilde{n}^2 \rangle} \quad !?$$

Fickian model bombs.....

Experiments: Modern 3

- The “mean jet velocity” of turbulence spreading $V_I = \frac{\langle \tilde{v}_r \tilde{n}^2 \rangle}{\langle \tilde{n}^2 \rangle}$ and *skewness* of density fluctuations show strong correlation



- Their trends and signs are consistent
- More work is being done on the *correlation between “blobs/holes” and turbulence spreading*

V_I - skewness trend follows joint reflection symmetry relation



$$x \rightarrow -x$$

$$\delta n \rightarrow -\delta n$$

cf. P.D., Hahm' 95

Spreading Pulses

- Avalanches, pulses are natural description

$\delta P \equiv$ deviation of profile from criticality

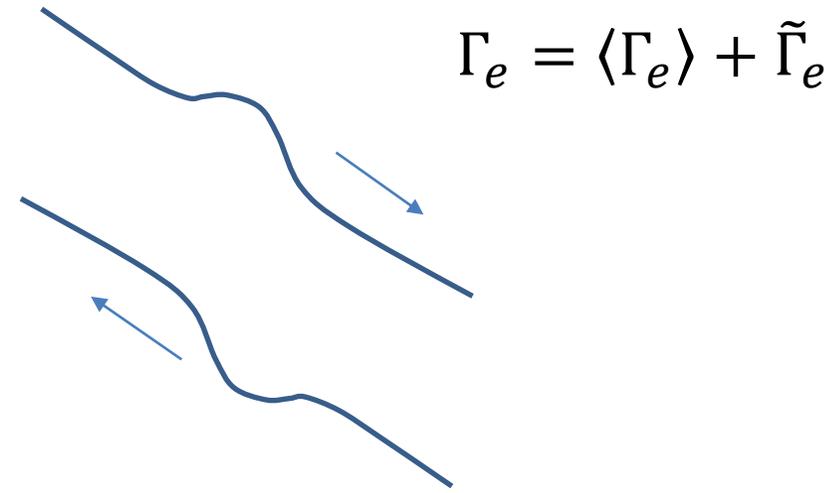
$$\delta P \leftrightarrow (\nabla P - \nabla P_{crit})/P$$

$$\delta P \sim \delta \varepsilon \sim \delta T$$

→ Spreading as intensity pulses dynamics

(after PD, Hahm '95)

- New:
 - Order parameter not conserved → finite SOL dwell time
 - V_D - mean curvature drift
 - $\Gamma_{0,e}|_{sep}$ drives system



Pulsation, void symmetry argument

Fluctuation Energy Pulses, cont'd

- Pulse model:

① drift

② dwell time decay

③ spreading

$$\partial_t \tilde{\varepsilon} + V_D \partial_x \tilde{\varepsilon} + \alpha \tilde{\varepsilon} \partial_x \tilde{\varepsilon} - D_0 \partial_x^2 \tilde{\varepsilon} + \frac{\tilde{\varepsilon}}{\tau} = 0$$

①
③
②

$\tilde{\varepsilon}(0, t) \leftrightarrow \tilde{\Gamma}_{sep}(t)$
regularization

Dwell rate damping regulates Pdf

$\tau \equiv$ SOL dwell time

Pulse energy *not* conserved in SOL

- Some limits:

– $\varepsilon \rightarrow 0$, $V_D \partial_x \tilde{\varepsilon} \sim \frac{\tilde{\varepsilon}}{\tau} \rightarrow \lambda \sim \lambda_{HD}$ scale (① vs ②)

– For ε to “matter” – i.e. broadening significant:

$\alpha \tilde{\varepsilon} > V_D \rightarrow$ amplitude vs neo drift comparison (① vs ③)

- Structure is Burgers + Krook \rightarrow ‘Crooked Burgers’
- Excitation by boundary (separatrix) flux.

Fluctuation Energy Pulses, cont'd

- Predictions ? → Goal Pdf(l | $\tilde{\Gamma}_{0,e}$)

structure
formation as
shock criterion

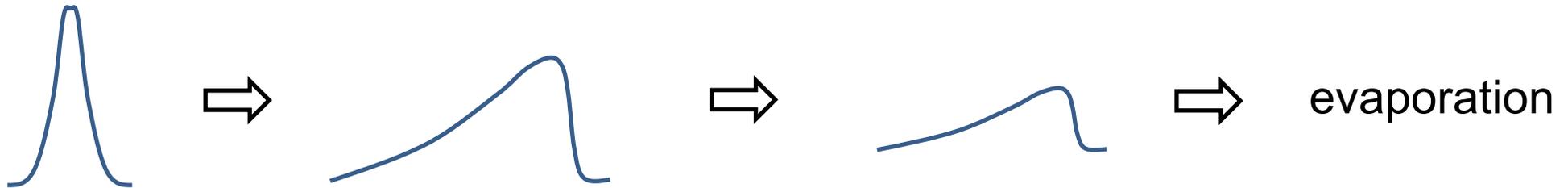
→ Pulse equation characteristics: $\frac{dx}{dt} = \alpha\varepsilon$, $\frac{d\varepsilon}{dt} \approx -\frac{\varepsilon}{\tau}$

Solution: Shock for $f'(z) < -1/\tau$

Initial slope steep enough to shock before damping by $1/\tau$

→ $\alpha \frac{\partial \varepsilon}{\partial x} < -\frac{1}{\tau}$ → separatrix intensity gradient defines pulse formation criterion

→ pulse evolution → penetration depth



∴ Pulse penetration depth Pdf is the output

Broader Messages

- Turbulence spreading is viable mechanism for broadening the stable SOL. Turbulent pedestal states attractive for heat load management.
- Theory indicates that can achieve $\lambda/\lambda_{HD} > 1$ for acceptable pedestal fluctuation levels. Trade-off analysis is critical.
- Spreading dynamics best treated statistically. Pdf(l_{pene}) is goal.
- Simulations should stress calculation of spreading fluxes, and Pdfs over color visualizations.

Thoughts for BOUT World

(by request)

Heat Loads (1)

- Calculate spreading, fluxes, Pdfs.

3D Brunner plot (Nami Li) is good start.

- High density is relevant regime.

SOL is conductive. $\tau_{dwell} \sim (Rq)^2 / \chi_{\parallel}$

λ_q increases but → density limit?! (Goldston)

∴ study high n regime where SOL instability restored.

SOL → pedestal spreading? H → L back transition?

- Pdf heat load distribution — λ_q ?!

Turbulence Spreading (2)

- Need improve fundamental understanding of turbulence spreading.

Present theory at “Fickian Diffusion” level \leftrightarrow primitive.

- *Investment* needed:

- BOUT++ 6-field model is “火锅”

- Try *detailed* study of *simpler* problems:

- 3-field model (ϕ, A_{\parallel}, p)

- 2D fluid

- Hasegawa-Wakatani (3D0)

- Consider fundamental experiment (Frontiers \rightarrow LAPD) collaboration.

cf. Compernelle +

Bout Code (3)

- Flux driven/source-sink version desperately needed. Critical on many fronts.

If GYSELA, why not BOUT++?

- Related: Avoid studies of states from marginal → likely unphysical
- Self-consistent hyper-resistivity evolution ↔
Multi-scale Ohm's Law (cf. P.W. Xi +)
- Implement toroidal rotation and its effect on V_E . Study physically meaningful E_r scans, explore intrinsic rotation, etc.

Thank you!

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