SOL Broadening by Edge Turbulence: Spreading and Entrainment Dynamics

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AAPPS-DPP (菊池祭) 2022 - CD

This research was supported by the U.S. Department of Energy, Office of Science, Office of Fusion Energy Sciences, under Award Number DEFG02-04ER54738.

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Acknowledge:

Nami Li, Jose Boedo, Zheng Yan, G. Tynan, X.-Q. Xu

Background

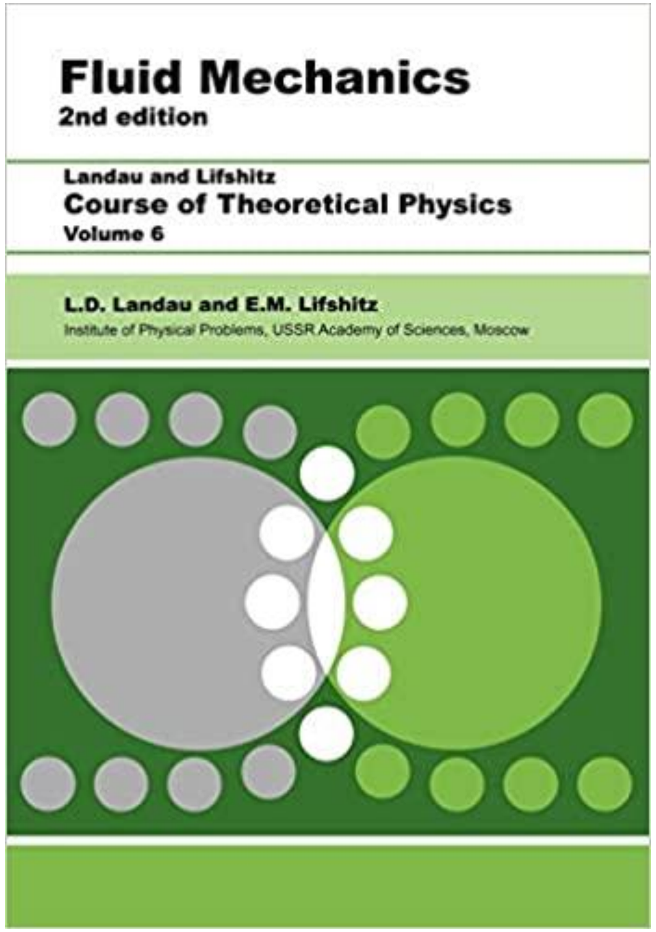
- Conventional Wisdom of SOL:

  (cf: Stangeby...)

  - Turbulent Boundary Layer, ala' Blasius, with D due turbulence
  - $\delta \sim (D\tau)^{1/2}, \tau \approx L_c/V_{th}$
  - $D \quad \leftrightarrow$ local production by SOL instability process

    → familiar approach, D ala' QL

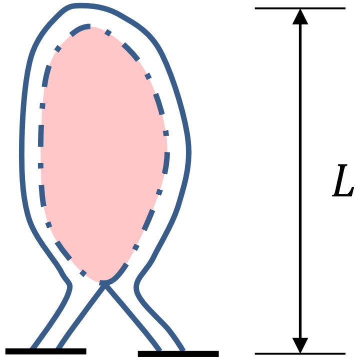
- Features:
  - Open magnetic lines → dwell time τ limited by transit, conduction, ala' Blasius
  - Intermittency → "Blobs" etc. Observed. Physics?



Fluid Mechanics
2nd edition

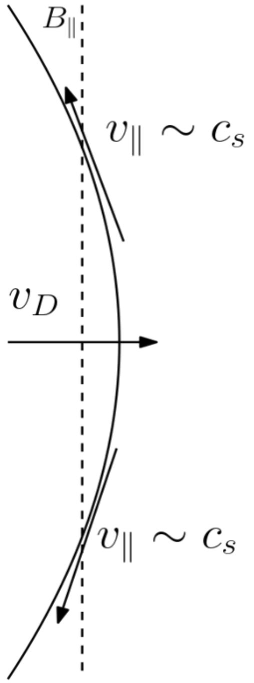
Landau and Lifshitz
Course of Theoretical Physics
Volume 6

L.D. Landau and E.M. Lifshitz
Institute of Physical Problems, USSR Academy of Sciences, Moscow



Background, cont'd

- But... Heuristic Drift (HD) Model (Goldston +)
  - $V \sim V_{\text{curv}}$, $\tau \sim L_c/V_{thi}$, $\boxed{\lambda \sim \epsilon\, \rho_{\theta i}}$ → SOL width
  - Pathetically small
  - Pessimistic B_θ scaling, yet high I_p for confinement
  - Fits lots of data.... (Brunner '18, Silvagni '20) → H-mode



- Why does neoclassical work? → ExB shear suppresses SOL modes i.e.

$$\gamma_{\text{interchange}} \sim \frac{c_s}{(R_c\lambda)^{\frac{1}{2}}} - \boxed{\frac{3T_{edge}}{|e|\lambda^2}}$$

shearing ←→ strong λ^{-2} scaling

$$\text{from: } \frac{c_s}{(R_c\lambda)^{\frac{1}{2}}} - \langle V_E\rangle'$$

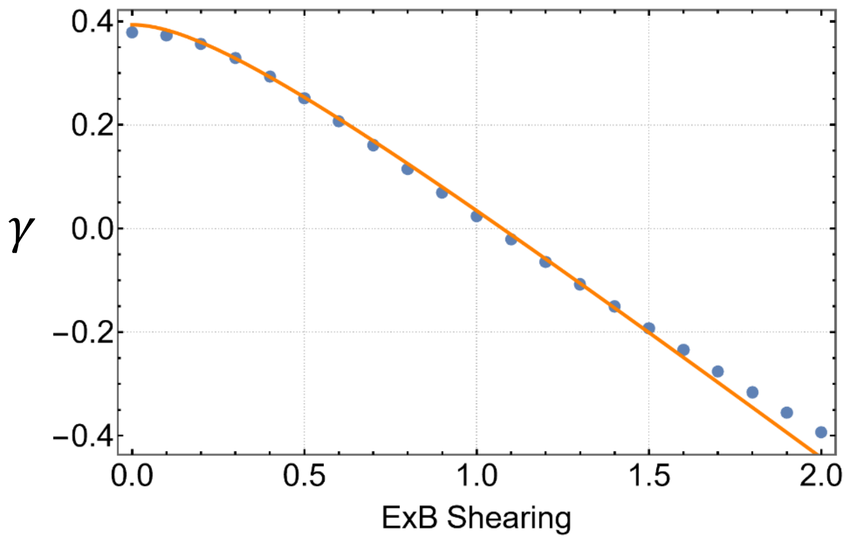
Physics Issues

[C.f. Chu, P.D., Guo, NF 2022]

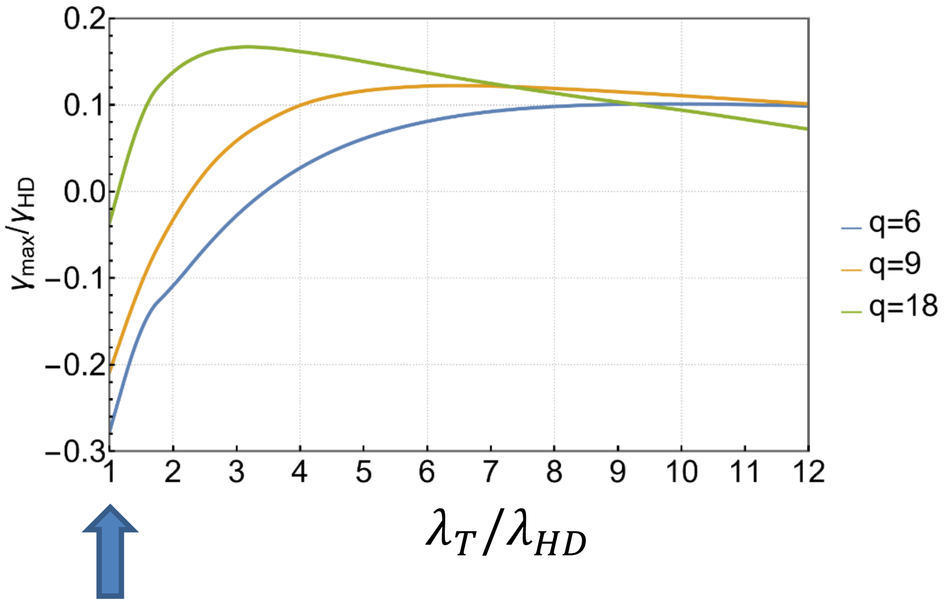
- How calculate SOL width for turbulent pedestal but a locally stable SOL?
  - spreading penetration depth
  - must recover HD in WTT limit
- ➡ Scaling and cross-over of λ_q relative to HD model
- ➡ What is effect/impact of barrier on spreading mechanism?
- Can SOL broadening and good confinement be reconciled ?

Model – Stable SOL – Linear Theory

- Standard drift-interchange with sheath boundary conditions + ExB shear (after Myra + Krash.)



Linear Growth Rate of a specific mode (fixed k_y) v.s. $E \times B$ shear at $q = 5, \beta = 0.001, k_y \cdot \lambda_{HD} = 1.58$.



Maximal Linear Growth Rate of Interchange Mode in the SOL v.s. normalized layer width λ_D/λ_{HD} at different SOL safety factor q (with $\beta = 0.001$)

- Relevant H-mode ExB shear strongly stabilizing $\gamma_{HD} = c_s/(\lambda_{HD} R)^{1/2}$
- Need λ/λ_{HD} well above unity for SOL instability. $V_E' \approx \frac{3T_e}{|e|\lambda^2}$ → layer width sets shear

Width of Stable SOL

- Fluid particle: $\frac{dV}{dt} = V_D + \tilde{V}$

  drift fluctuating velocity

- Dwell time: $\tau_\parallel$ dwell time contrains excursion

$$\delta^2 = \langle \left(\int \left(V_D + \tilde{V} \right) dt \right) \left(\int \left(V_D + \tilde{V} \right) dt \right) \rangle$$

$$= V_D^2 \tau_\parallel^2 + \langle \tilde{V}^2 \rangle \tau_c \tau_\parallel$$

τ_c cut-off at $\tau_\parallel$

$$\approx \lambda_{HD}^2 + \varepsilon\, \tau_\parallel^2$$

- So $\boxed{\lambda = \tau_\parallel \left[V_D^2 + \varepsilon \right]^{1/2}}$ SOL width effects add in quadrature
- How compute ε ? → turbulence energy in SOL ?

Calculating the SOL Turbulence Energy 1

- $K - \epsilon$ type model, mean field approach (c.f. Gurcan, P.D. ’05 et seq)
  - Can treat various NL processes via σ, κ
  - Exploit conservative form model
- $\partial_t \varepsilon = \gamma \varepsilon - \sigma \varepsilon^{1+\kappa} - \partial_x \Gamma_e$ → Spreading, turbulence energy flux

Growth $\gamma < 0$
here contains shear + sheath

NL transfer $\gamma_{NL} \sim \sigma \varepsilon^{\kappa}$

- N.B.: No Fickian model of Γ_e employed
- Readily extended to 2D, improved production model, etc.

Calculating the SOL Turbulence Energy 2

- Integrate ε equation $\int_0^\lambda$
- Take quantities = layer average
- $\Gamma_{e,0} + \lambda_e \gamma \varepsilon = \lambda_e \, \sigma \, \varepsilon^{1+\kappa}$

Separatrix fluctuation energy flux → Single parameter characterizing spreading

So for $\gamma < 0$,

$$\boxed{\Gamma_{e,0} = \lambda_e |\gamma| \varepsilon + \sigma \lambda_e \varepsilon^{1+\kappa}}$$

λ_e = layer width for ε

$\Gamma_{e,0}$ vs linear + nonlinear damping

Calculating the SOL Turbulence Energy 3

[Mean Field Theory]

- Full system:

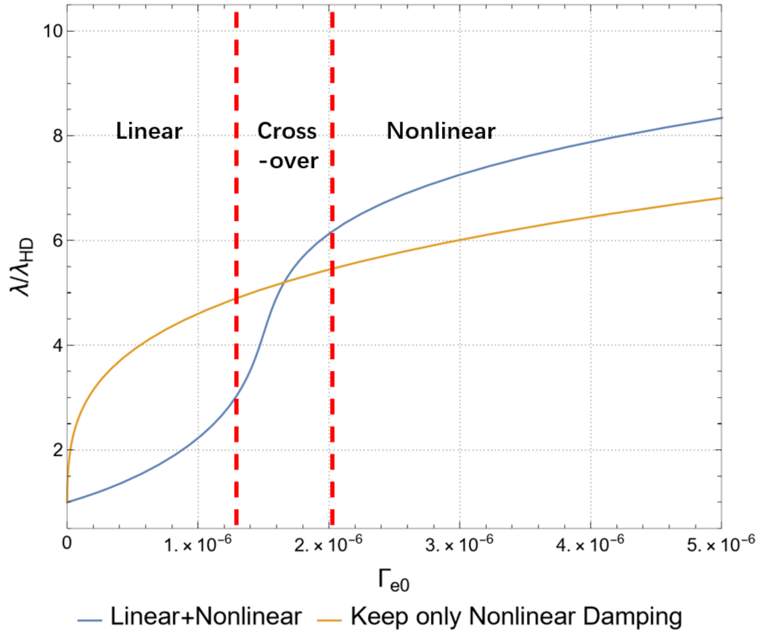
$$\boxed{\begin{gathered}\Gamma_{e,0} = \lambda_e |\gamma| \varepsilon + \sigma \lambda_e \varepsilon^{1+\kappa} \\ \lambda_e = \left[\lambda_{HD}^2 + \varepsilon \tau_{\parallel}^2\right]^{1/2}\end{gathered}}$$

Simple model of turbulent SOL broadening

- $\Gamma_{0,e}$ is single control parameter characterizing spreading
- $\tilde{\Gamma}_{0,e}$? Expect $\tilde{\Gamma}_e \sim \Gamma_0$

SOL width Broadening vs $\Gamma_{e,0}$

- SOL width broadens due spreading



(blue) (orange)

λ/λ_{HD} plotted against the intensity flux Γ_{e0} from the pedestal at $q = 4, \beta = 0.001, \kappa = 0.5, \sigma = 0.6$

Variation indicates need for detailed scaling analysis

- Clear decomposition into
  - Weak broadening regime → shear dominated
  - Cross-over regime
  - Strong broadening regime

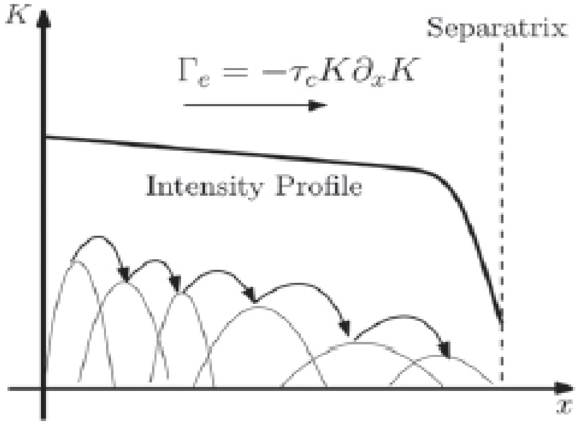
➔ NL damping vs spreading

relevant

- Cross-over for: $\Gamma_{0,e}$ sufficient s/t $\langle \tilde{V}^2 \rangle \sim V_D^2$
- Cross-over for $\tilde{V} \sim O(\epsilon) V_*$

➔ weak turbulence

Computing the Turbulence Energy Flux 1



- Need consider pedestal to actually compute $\Gamma_{e,0}$
- Two elements

Does another trade-off loom?

-- Pedestal Turbulence: Drift wave? Ballooning?

-- Effect of transport barrier ←→ ExB shear layer ➔ barrier permiability!?

- Key Point: shearing limits correlation in turbulent energy flux

i.e. $\Gamma_{e,0} \approx -\tau_c \, I \, \partial_x \, I \approx \tau_c \, I^2 \, / w_{\text{ped}}$ (Hahm, PD +)

ped turbulence intensity

correlation time → strongly sensitive to shearing

N.B. Caveat Emptor re: intensity flux closure !

Computing the Turbulence Energy Flux 2

- Familiar analysis for D → Kubo

$$D = \int_0^\infty d\tau \, \langle V(0)V(\tau)\rangle = \int_0^\infty d\tau \sum_k \left|\tilde{V}_k\right|^2 \exp\left[-k_y^2 \omega_s^2 D \tau^3 - k^2 D \tau\right]$$

- Strong shear (relevant) $\boxed{\tau_c = \tau_t^{1/2} \omega_s^{-1/2}}$

$\tau_t \sim 1 \,/\, k\tilde{V}, \quad \omega_s \sim V_E'$

Here, via RFB ➔ $\omega_s = \partial_r \frac{\nabla P_i}{n|e|} \sim \frac{\rho^2}{w_{ped}^2} \Omega_{ci}$

- $\tau_c + w_{ped}$ + turbulence intensity in pedestal gives $\Gamma_{e,0} \approx \tau_c I^2 / w_{ped}$
- Need $\Gamma_{e,0} \geq \Gamma_{e,\min} \approx |\gamma| \lambda_{HD}^3 \, \tau_\parallel^{-2}$

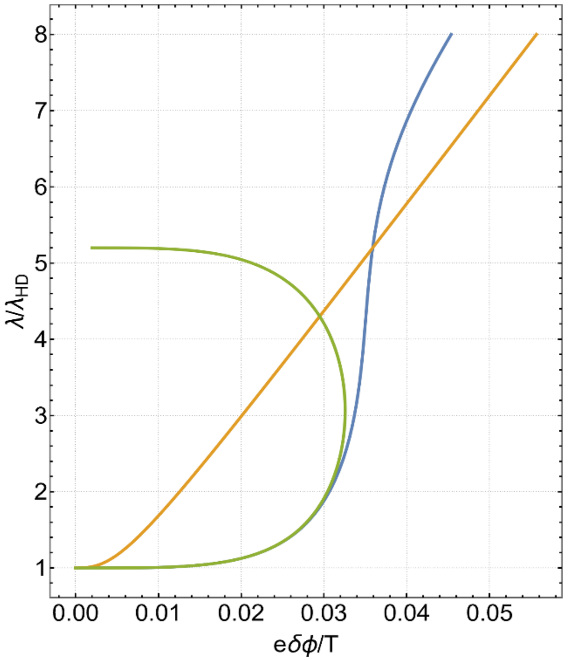
Computing the Turbulence Energy Flux 3

- Pedestal → Drift wave Turbulence
- Necessary turbulence level:
  - Weak Shear $\frac{\delta V}{c_s} \sim \left(\frac{\rho}{R}\right)^{1/2} q^{-1/4}$
  - Strong Shear $\frac{\delta V}{c_s} \sim \left(\frac{\rho}{R}\right)^{1/2} q^{-1/4} \left(\frac{w_{ped}}{\rho}\right)^{-1/8}$

blue – all damping

orange – nonlinear only

green – linear only



➔ λ/λ_{HD} vs $|e|\hat{\phi}/T_e$ in pedestal

➔ ρ/R is key parameter

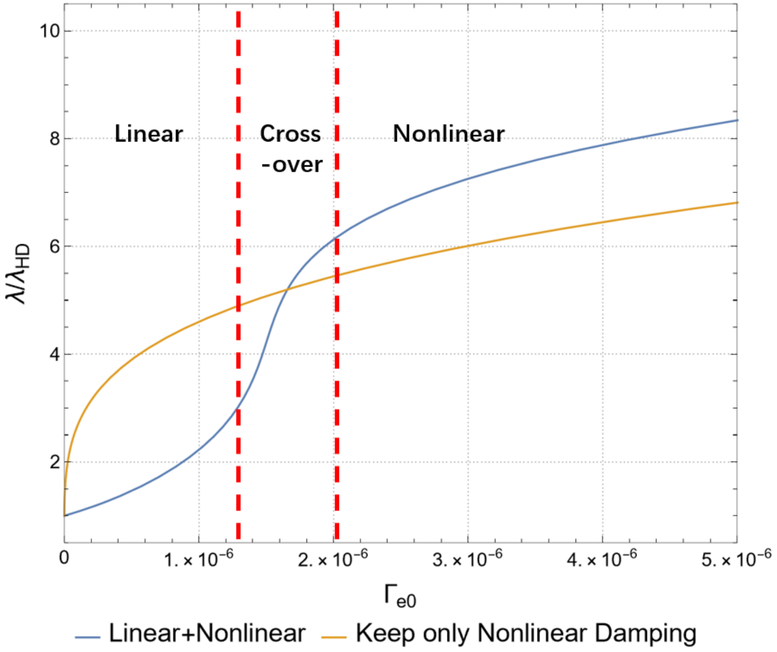
➔ Broadens layer at acceptable fluctuation level

Partial Summary

- Turbulent scattering broadens stable SOL

$$\lambda = \left(\lambda_{HD}^2 + \varepsilon\tau_{\parallel}^2\right)^{1/2}$$

- Separatrix turbulence energy flux specifies SOL turbulence drive



$$\Gamma_{0,e} = \lambda_e|\gamma|\varepsilon + \lambda\sigma\varepsilon^{1+\kappa}$$

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

Non-trivial dependence

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

Yes – can broaden SOL to $\lambda/\lambda_{MHD} > 1$ at tolerable fluctuation levels

Further analysis needed

Broader Messages

- Turbulence spreading is important – even dominant – process in setting SOL width. $\Gamma_{0,e}$ is critical element. $\lambda = \lambda(\Gamma_{0,e}, \mathrm{parameters})$
- Production Ratio R_a merits study and characterization
- Spreading is important saturation meachanism for pedestal turbulence
- Simulation should stress calculation and characterization of turbulence energy flux over visualizations and front propagation studies.
- Critical questions include local vs FS avg, channels and barrier interaction, Turbulence ‘Avalanches’
- Turbulent pedestal states attractive for head load management

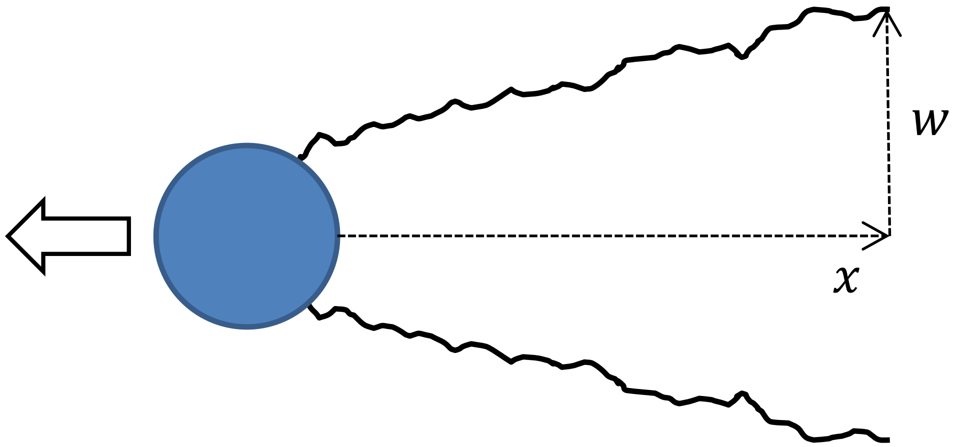
Physics of Turbulence Spreading: General Perspective

- Structure of the intensity flux-gradient relation(?)

- Spreading as directed percolation…

Spreading: Conventional Wisdom

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



Mixing length model

Similarity theory

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

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

C_D → indep ν

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

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

How render tractable ?

Spreading: cont'd

- What you get (usually):

$$\partial_t \varepsilon + \vec{V}_D \cdot \nabla \varepsilon + \langle \vec{V}_E(r) \rangle \cdot \nabla \varepsilon - \partial_r D(\varepsilon) \partial_r \varepsilon = P(\varepsilon) - P_{\mathrm{damp}}(\varepsilon) \rightarrow \gamma(\vec{x})\varepsilon$$

drift

shear

turbulent mixing via closure

$\gamma = \gamma$(gradients, etc)

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

→ ε evolution as nonlinear Reaction-Diffusion Problem!

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

- Used also in:
  - BLY-style layering models (Ashourvan)
  - 1D L→H models (Miki)

Spreading: cont'd

- Spreading as Front ➔ Fast Propagation

  i.e. $V_f \sim (\gamma D)^{1/2}$, etc [N.B. Cahn-Hilliard?]

- Key component:

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

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

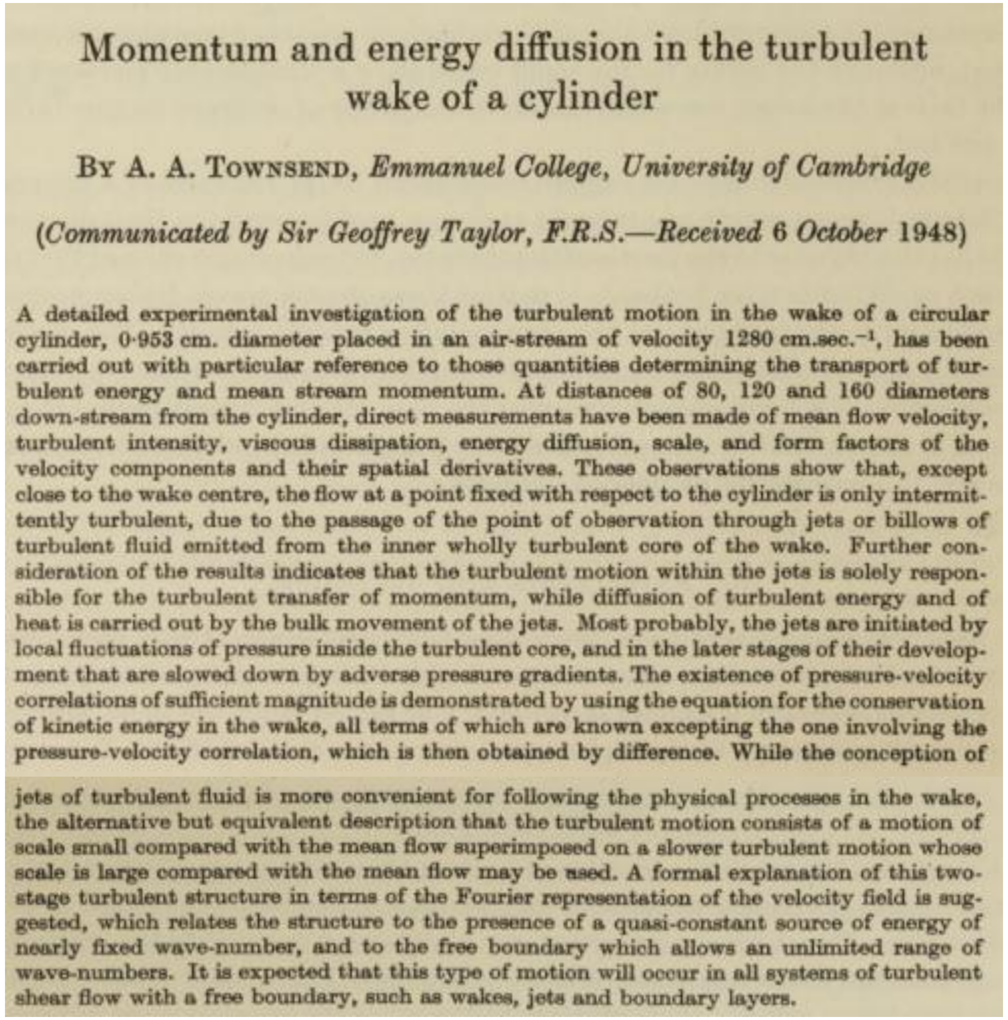
- Copious simulations: Z. Lin, W.X. Wang, S. Yi, Jae-Min Kwon, Y. Sarazin, …

➔ Observations, front tracking but critical analysis of model absent ??

No test of Fickian flux model !

Experiments: Ancient

- Not exactly a new idea … See Townsend ‘49 and book



Momentum and energy diffusion in the turbulent wake of a cylinder

By A. A. Townsend, *Emmanuel College, University of Cambridge*

(*Communicated by Sir Geoffrey Taylor, F.R.S.—Received 6 October* 1948)

A detailed experimental investigation of the turbulent motion in the wake of a circular cylinder, 0·953 cm. diameter placed in an air-stream of velocity 1280 cm.sec.$^{-1}$, has been carried out with particular reference to those quantities determining the transport of turbulent energy and mean stream momentum. At distances of 80, 120 and 160 diameters down-stream from the cylinder, direct measurements have been made of mean flow velocity, turbulent intensity, viscous dissipation, energy diffusion, scale, and form factors of the velocity components and their spatial derivatives. These observations show that, except close to the wake centre, the flow at a point fixed with respect to the cylinder is only intermittently turbulent, due to the passage of the point of observation through jets or billows of turbulent fluid emitted from the inner wholly turbulent core of the wake. Further consideration of the results indicates that the turbulent motion within the jets is solely responsible for the turbulent transfer of momentum, while diffusion of turbulent energy and of heat is carried out by the bulk movement of the jets. Most probably, the jets are initiated by local fluctuations of pressure inside the turbulent core, and in the later stages of their development that are slowed down by adverse pressure gradients. The existence of pressure-velocity correlations of sufficient magnitude is demonstrated by using the equation for the conservation of kinetic energy in the wake, all terms of which are known excepting the one involving the pressure-velocity correlation, which is then obtained by difference. While the conception of jets of turbulent fluid is more convenient for following the physical processes in the wake, the alternative but equivalent description that the turbulent motion consists of a motion of scale small compared with the mean flow superimposed on a slower turbulent motion whose scale is large compared with the mean flow may be used. A formal explanation of this two-stage turbulent structure in terms of the Fourier representation of the velocity field is suggested, which relates the structure to the presence of a quasi-constant source of energy of nearly fixed wave-number, and to the free boundary which allows an unlimited range of wave-numbers. It is expected that this type of motion will occur in all systems of turbulent shear flow with a free boundary, such as wakes, jets and boundary layers.

➔ Wake flow intermittently turbulent

➔ Compare transport of momentum and energy (spreading)

Experiments: Ancient, cont'd

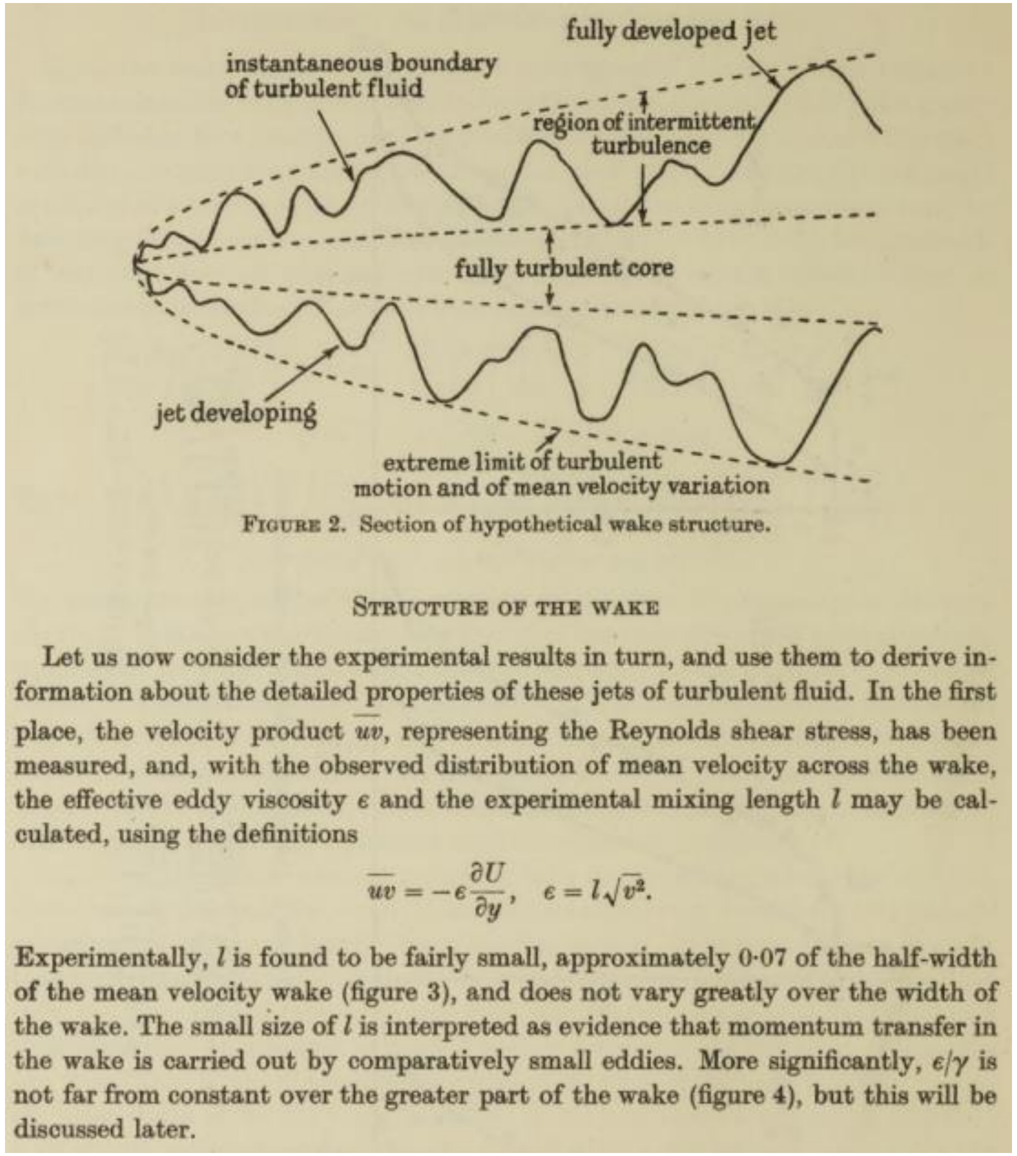


FIGURE 2. Section of hypothetical wake structure.

STRUCTURE OF THE WAKE

Let us now consider the experimental results in turn, and use them to derive information about the detailed properties of these jets of turbulent fluid. In the first place, the velocity product $\overline{uv}$, representing the Reynolds shear stress, has been measured, and, with the observed distribution of mean velocity across the wake, the effective eddy viscosity ϵ and the experimental mixing length l may be calculated, using the definitions

$$\overline{uv} = -\epsilon \frac{\partial U}{\partial y}, \quad \epsilon = l\sqrt{\overline{v^2}}.$$

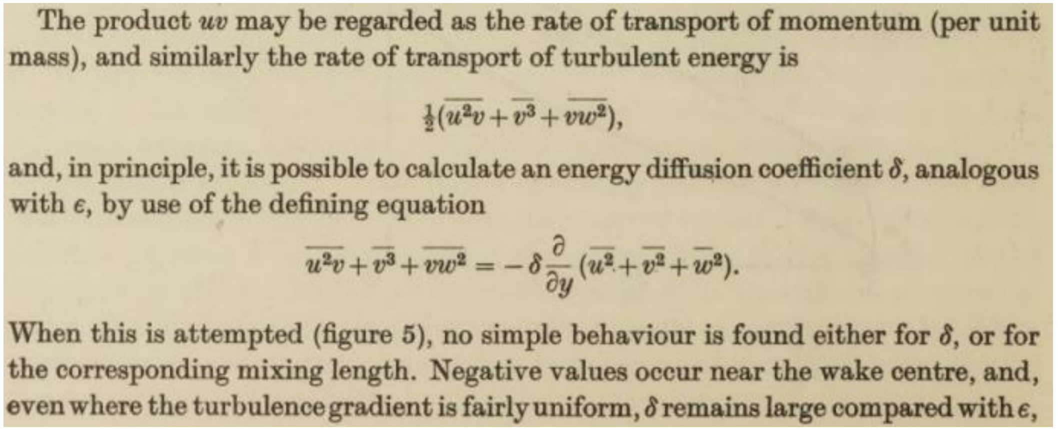
Experimentally, l is found to be fairly small, approximately 0·07 of the half-width of the mean velocity wake (figure 3), and does not vary greatly over the width of the wake. The small size of l is interpreted as evidence that momentum transfer in the wake is carried out by comparatively small eddies. More significantly, ϵ/γ is not far from constant over the greater part of the wake (figure 4), but this will be discussed later.

➔ Wake expansion due jets of expanding fluid

➔ Departs mean field theory

➔ Mixing length model momentum transport

Experiments: Ancient, cont’d



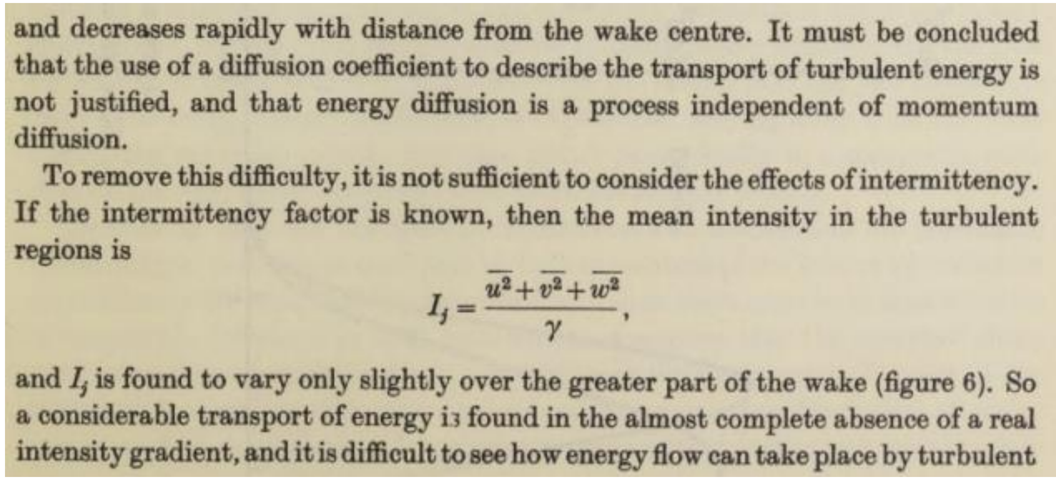
The product uv may be regarded as the rate of transport of momentum (per unit mass), and similarly the rate of transport of turbulent energy is

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

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,

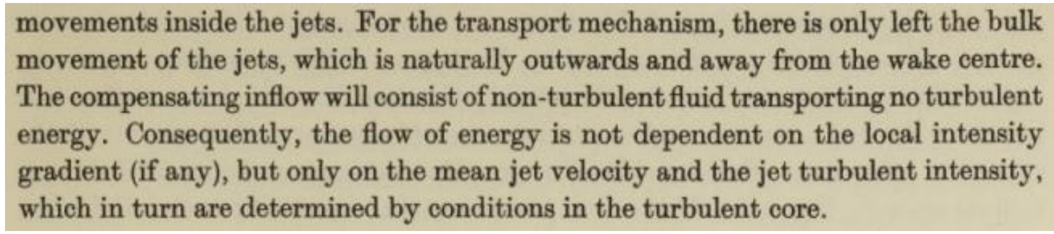


and decreases rapidly with distance from the wake centre. It must be concluded that the use of a diffusion coefficient to describe the transport of turbulent energy is not justified, and that energy diffusion is a process independent of momentum diffusion.

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”

Experiments: Modern (Ting Long, SWIP) 1

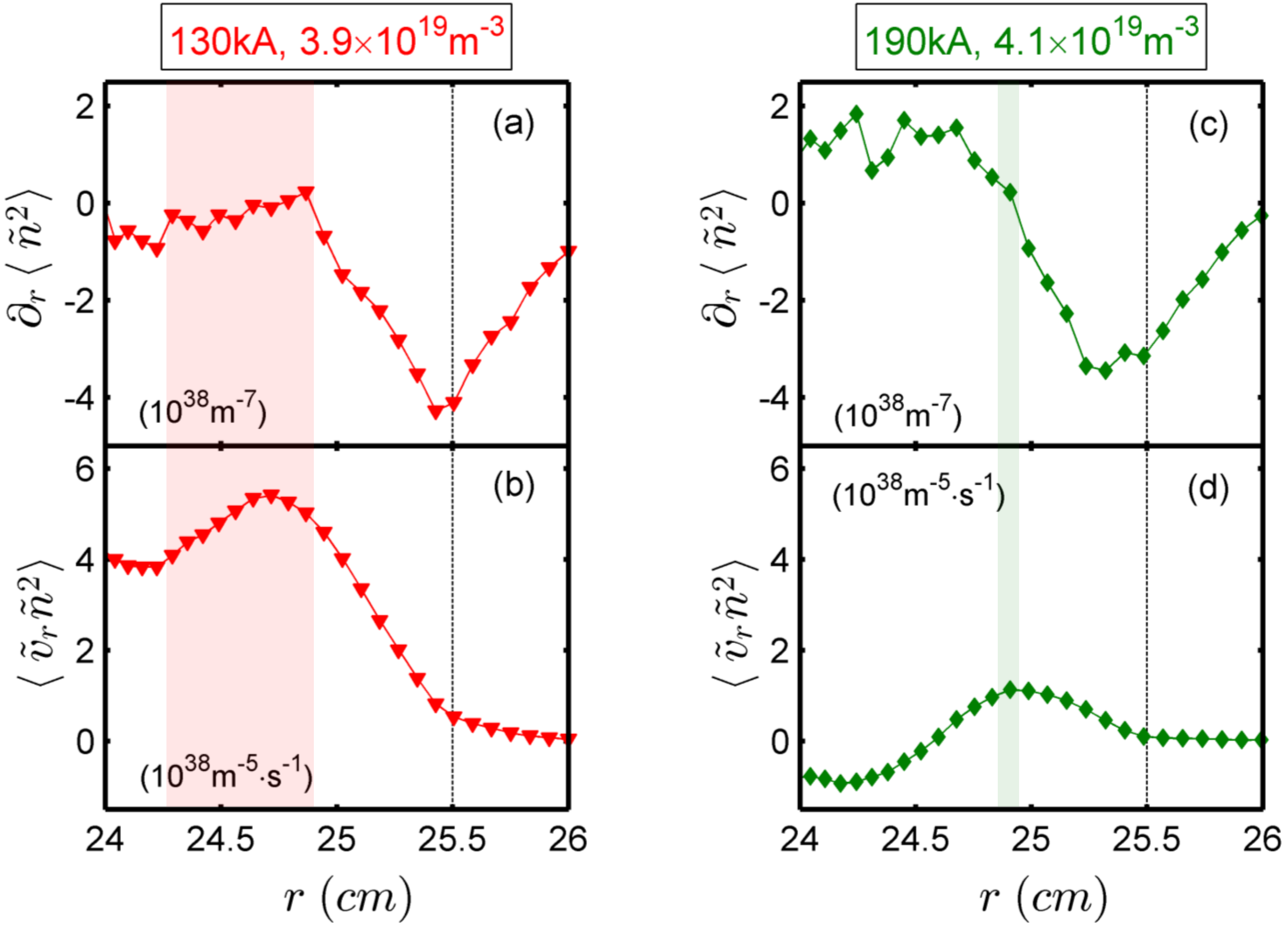
- HL-2A
- Aims:
  - Exploration of intensity flux – intensity gradient relation in edge turbulence (exploits spreading, shear layer collapse and density limit studies Long + NF’21)
  - Physics of “Jet Velocity” profile

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

N.B. Identified by Townsend

Experiments: Modern 2

- There exits 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**



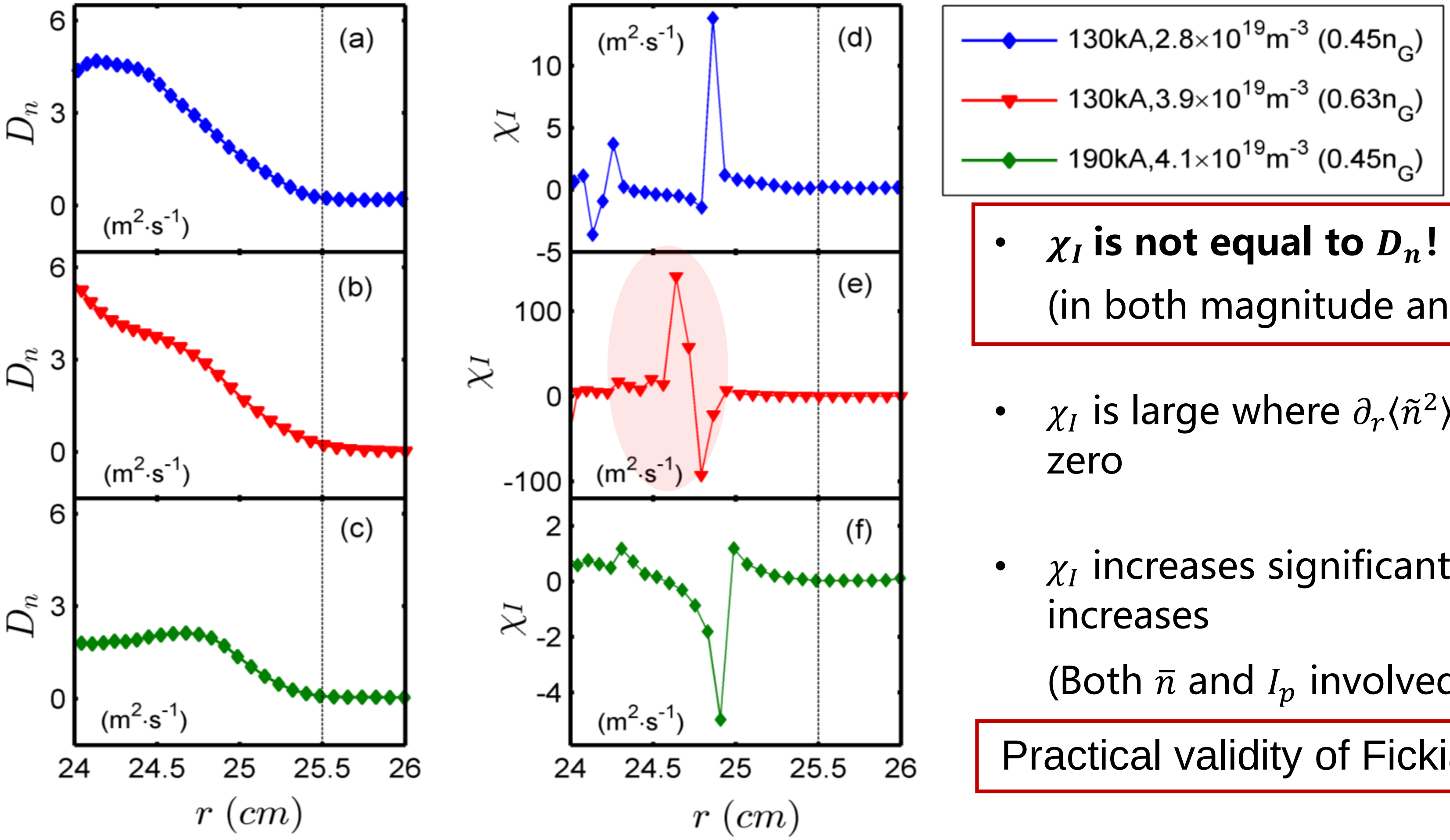
For close $\bar{n}_e$

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

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

Experiments: Modern 3

- Striking difference between particle diffusivity and energy spreading diffusivity
  - Diffusivity of turbulent particle flux $\langle \tilde{n}\tilde{v}_r \rangle = -\boxed{D_n}\,\partial_r \langle n \rangle$
  - Diffusivity of turbulence spreading $\langle \tilde{v}_r \tilde{n}^2 \rangle = -\boxed{\chi_I}\,\partial_r \langle \tilde{n}^2 \rangle$



- **χ_I is not equal to D_n!**
  (in both magnitude and sign)

- χ_I is large where $\partial_r \langle \tilde{n}^2 \rangle$ is near zero

*

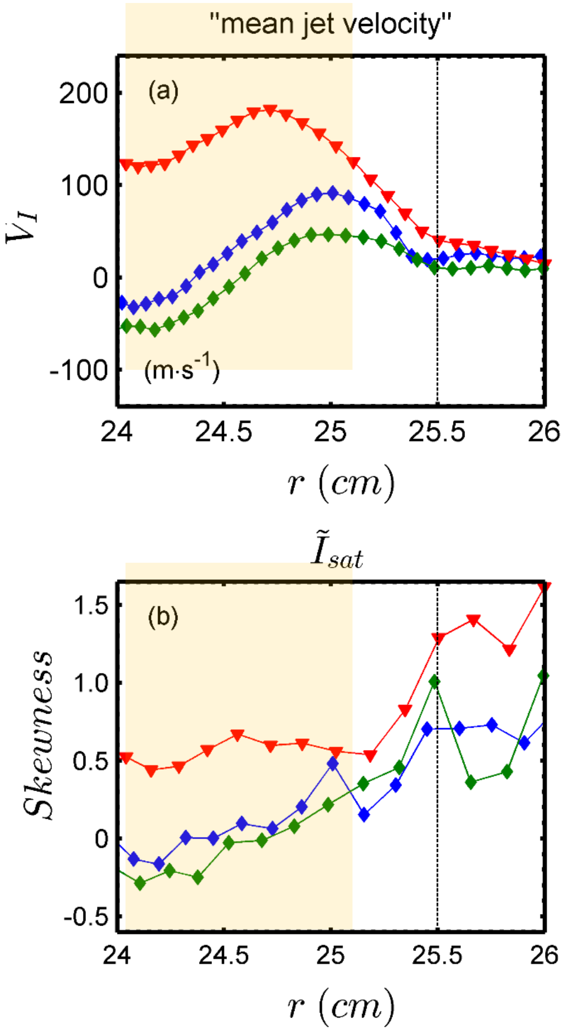
- χ_I increases significantly as $\bar{n}/n_G$ increases

  (Both $\bar{n}$ and I_p involved)

Practical validity of Fickian model is dubious

Experiments: Modern 4

- 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

Spreading as Fluctuation Intensity Pulses

- Edge turbulence intermittent → mean field theory?
  - – Strong $\langle V_E \rangle'$ → ~ marginal avalanching state
  - – Weaker $\langle V_E \rangle'$ → structures, etc. $\Gamma_e = \langle \Gamma_e \rangle + \tilde{\Gamma}_e$
- Pulses / Avalanches are natural description

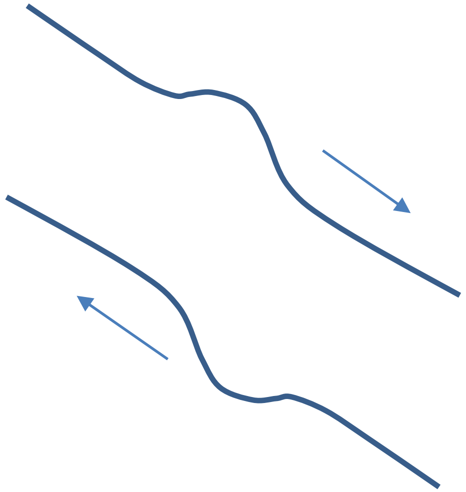
$\delta P \equiv$ deviation of profile from criticality

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

Naturally: $\delta P \; \sim \; \delta \varepsilon$

→ Spreading as intensity pulses

(after Hwa, Kardar, P.D., Hahm)



Pulse, void symmetry arguments etc.

Fluctuation Energy Pulses, cont'd

- Burgers is on the grill…
- New toppings:
  - $\delta\varepsilon > 0$ turbulence ejected into SOL

    positive intensity fluctuation
  - $V_D > 0$ mean drift out – curvature
- * Scale independent damping
  - $(1/\tau)\delta\varepsilon$ due finite dwell time in SOL → order parameter not conserved
- Noise is b.c.
  - $\tilde{\Gamma}_{0,e}|_{sep}$ drives system, space-time

Fluctuation Energy Pulses, cont'd

- Pulse model:

  ① drift

  ② dwell time decay

  ③ spreading

$$\partial_t\tilde{\varepsilon} + \overset{\text{①}}{V_D\partial_x\tilde{\varepsilon}} + \overset{\text{③}}{\alpha\tilde{\varepsilon}\partial_x\tilde{\varepsilon}} - D_0\partial_x^2\tilde{\varepsilon} + \overset{\text{②}}{\frac{\tilde{\varepsilon}}{\tau}} = 0$$

regularization

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

- 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:

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

- Structure is Burgers + Krook → Crooked Burgers

Fluctuation Energy Pulses, cont'd

- Predictions?

Structure formation → Shock Criterion !

i.e. Recall: $\frac{d\varepsilon}{dt} = -\frac{\varepsilon}{\tau}$, $\frac{dx}{dt} = \alpha\varepsilon$

- Solve via characteristics:

$$x = \alpha\left[z + \frac{\left(1-e^{-\frac{t}{\tau}}\right)}{(1/\tau)} f(z)\right]$$

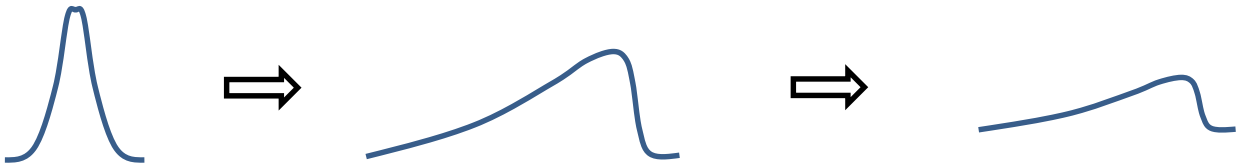
Shock for: $f'(z) < -1/\tau$

→ inital slope must be sufficiently steep to shock before damped by $1/\tau$

Spreading as Fluctuation Intensity Pulses, cont'd

- $\alpha \frac{\partial \varepsilon}{\partial x}|_{sep} < -\frac{1}{\tau}$ → pulse formation criterion → intensity gradient

- Fate ?



  $\alpha\ \varepsilon < V_D$ → defacto 'evaporation criterion'

  → defines penetration depth of pulse

- Aim to characterize statistics of pulses, penetration depth distribution… in terms Pdf($\tilde{\Gamma}_{0,e}$) . Challenging…

  ➔ Meaningful output for SOL broadening problem

Directed Percolation - Remark

- Goldenfeld Rosenbluth lecture, Festival de Theorie ‘17

  ➔ Fundamentally, spreading as a directed percolation process…

- D.P. as P. with sense of time’s arrow

  D.P. ←→ avalanching… → pulses

  BTW ‘87 interprets SOC state as percolation cluster, critical to addition of single grain

e.g. Do avalanches span system?

- Mean field models of DP → reaction diffusion, hydrodynamics

But…

- Fluctuations <u>significant</u> near criticality !

  ➔ R. G. … TBC …

Open Issues

- Quantify $\lambda = \lambda\left(\frac{|e|\hat{\phi}}{T}\bigg|_{ped}\right)$ dependence
- Structure of Flux-Gradient relation for turbulence energy?
- Phase relation physics for intensity flux? – crucial to ExB shear effects
- Kinetics → $\langle \tilde{V}_r \delta f \delta f \rangle$, Local vs Flux-Surface Average, EM
- SOL Diffusive? → Intermittency('Blob'), Dwell Time ?
- SOL → Pedestal Spreading ? ←→ HDL (Goldston) ?

  i.e. Tail wags Dog ? Both wagging ? → Basic simulation, experiment ?

  Counter-propagating pulses ?

Some Concluding Philosophy

- MFE relevant questions within reach in near future. Great attention to λ_q problem (c.f. Samuel Johnson)
- Unreasonable for tokamak experiments to probe ~ critical dynamics so as to elucidate basic questions. Simulations???
- Well diagnosed, basic experiment with some relevant features are sorely needed – akin to ‘Tube’ studies of flows, ala’ CSDX
- How?