# Our Evolving Understanding of Tokamak Confinement Physics:

# Thoughts for the 80th Birthday of Roald Z. Sagdeev

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# Outline

A.) 1) Foundations: Sagdeev's Greatest Hits

→ The Building Blocks of Confinement Theory

2) Where Things Stand Today:

→ Current Status of Our Understanding: An OV

B.) A Recent Perspective:

→ Heat Flux 'Jamitons' and the Formation of

the E x B staircase

- with Yusuke Kosuga and Ozgur Gurcan

C.) Looking Ahead

# A1.) Sagdeev's Greatest Hits in MFE

i.) Microstability Theory

– basic physics of drift and ITG modes

→ early - mid 60's

→ with: Rosenbluth, Rudakov, Moiseev, Coppi, …

(Coppi, MNR, RZS '67)

achieved:

– 'inverse dissipation' mechanism for electron drift waves

– 'negative compressibility' ITG modes

– first effects of magnetic geometry

➔ Defined fundamental agents of core anomalous transport: ITG, CTEM ii.) Quasilinear (Mean Field) Theory

→ early - mid 60's

→ with: Vedenov, Velikov, …

achieved:

– mean field theory for Vlasov system

– basic wave-particle energetics

– time scale hierarchy and link to chaos

➔ Formulated basis of all transport models currently in use in MFE community iii.) Weak Turbulence Theory, especially nonlinear wave-particle interaction

→ early - mid 60's => Trieste lectures

→ with: Galeev, Rudakov, Zakharov, Shapiro, …

achieved:

– complete perturbative theory of non-linear dynamics, with wave-wave and wave-particle interaction on an equal footing

– initial ideas on quasi-particle models

– set foundations for subsequent work on granulations, strong turbulence (T. H. Dupree, et al.)

➔ defined the structure. Potential use for G.K. verification not yet exploited.

iv.) Hamiltonian Chaos

→ early 60's – 80's

→ with: Zaslavsky, Rosenbluth, Taylor (RSTZ paper, Trieste) …

achieved:

→ formulation of Hamiltonian chaos theory for plasma-relevant problems, especially magnetic field lines (c.f. Rechester-Rosenbluth '78)

→ linked Kolmogorov, Arnold, Chirikov to MFE-plasma community

→ initiated further work by Zaslavsky school

➔ defined and established standard techniques in everyday use – re: RMP v.) Neoclassical Theory

→ 60's

→ with: Galeev, Rosenbluth, …

achieved:

– basic structure and concepts of the theory

– fundamental ideas on heat transport, flow damping, electric fields, …

➔ conceptual foundations of an industry initiated, followed by many others vi.)  Quasi-Particle Picture and Methodology

→  60's – late 70's

→  with: Zakharov, Rudakov, Galeev, Shapiro, Shevchenko, …

achieved:

– development of modulational interaction paradigm

  → Langmuir turbulence

  → convective cells (includes zonal flows)

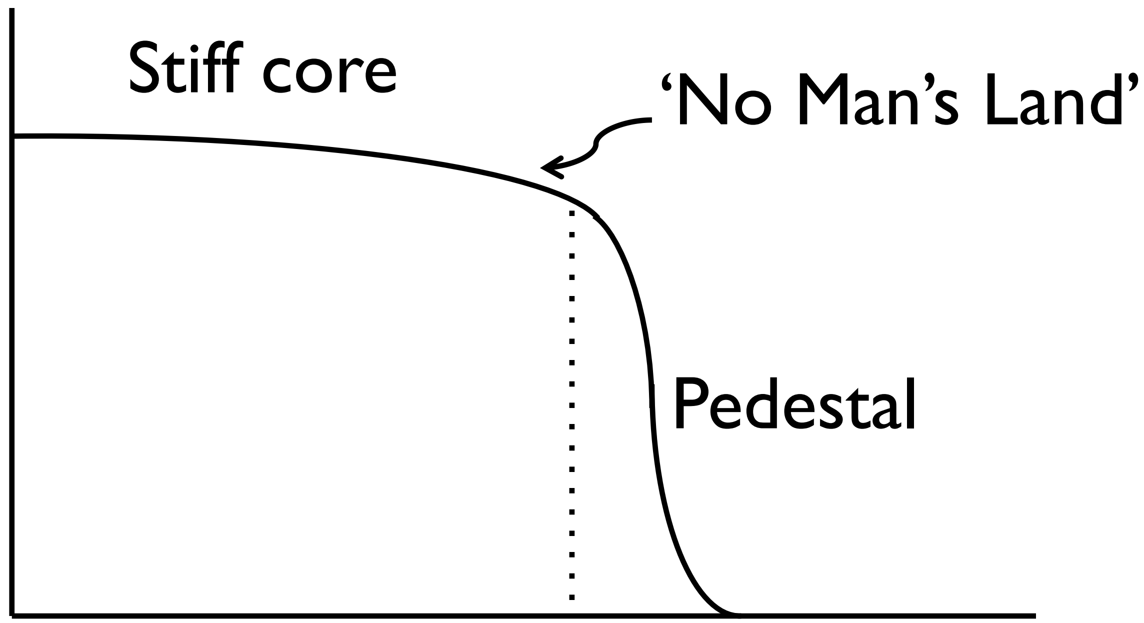
    cf: Sagdeev, et al. '78

– concept of pattern selection in secondary structures

➔ mapped out a useful and elegant approach to structure formation in turbulence

# A2.) Where Things Stand Today

→ The Multi-Zone Picture




– core: Stiff / No Man's Land

– edge/ pedestal

<u>Core:</u>

– The Good News – Understanding

→ Core Turbulence : ITG, TEM modes ("standard model")

→ $D \sim D_B \rho_*^{\alpha}, \ \alpha \leq 1$ ➔ close to GyroBohm

→ Zonal Modes critical to saturated state

→ $\nabla n$ peaking ➔ TEP, thermoelectric pinch

→ intrinsic rotation ➔ turbulent (residual) stress

→ The Bad News – Performance

→ Stiffness ➔ Core profiles difficult to move off criticality

→ No Man's Land:
- standard GK codes under-predict layer linking pedestal to stiff core
- "standard model" fails
- spreading, non-locality?
- Significant impact on ITER predictions

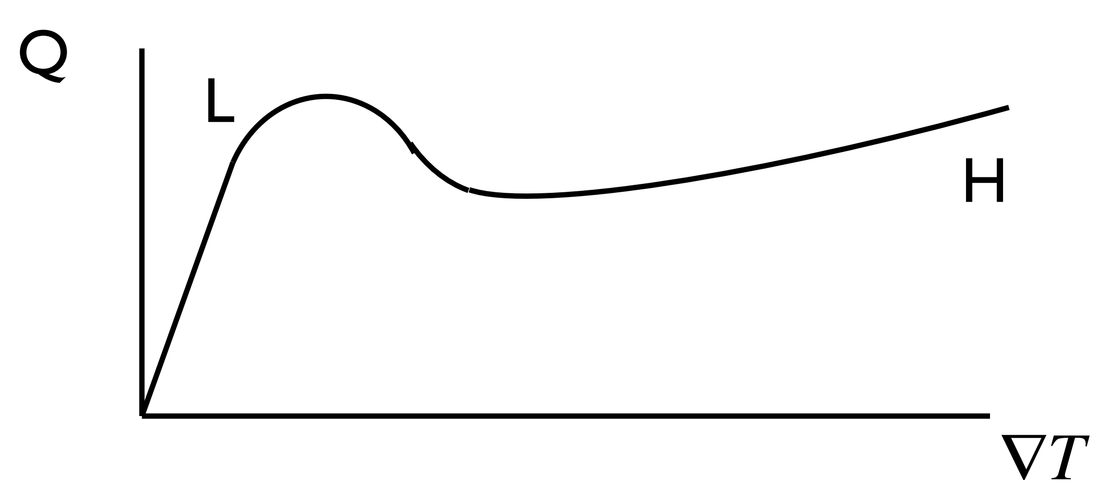
→ 'The Fix' – of questionable reactor relevance : ITBs
- ITB's require externally driven $V_{\Phi}$ shear→ how ?
- MHD stability of ITB plasmas dubious

➔ We understand a great deal about the core, but will probably need to live with its stiffness…

## Edge

→ Good News ➔ H-Mode

- L→H transition, first observed in 1982, by F. Wagner on ASDEX, is THE high point of MFE since Trieste.
- L→H transition enables confinement with plausible extrapolation to ignition, and is 'robust' state.
- physics : H-mode is due spontaneous ETB formation, very likely due to enhanced ExB shear suppression induced transport bifurcation.



→ Current Status :

- L→H transition likely triggered by synergy between Reynolds stress driven (zonal) flows and $\nabla P$-driven diamagnetic flow

  ➔ world wide ‘hot topic’, especially 2009 - present

- Transition is 1st order ➔ hysteresis

Major unknowns :

- $P_{Thresh}(r)$ scalings, especially low density regime
- strength of hysteresis ➔ important near $P_{Th}$
- width of H-mode pedestal
- pedestal transport physics → especially electron thermal

→ The Bad News ➔ H-Mode

- H-mode is fundamentally state with strong suppression of particle transport
- $\nabla n$ and $\nabla P$ steepen to (MHD) stability limits

➔ ELMs happen!

- ELM : Edge Localized Modes
  - edge relaxation oscillation
  - kink-ballooning, etc.
  - unacceptable transient power load on PFC
- Basic Problem: H-mode (Particle) Confinement is

TOO GOOD.

→ ITER Crisis Du Jour – ELM Mitigation

- Seek reduce/eliminate ELM by relieving $\nabla P$ using stochastic field induced by additional applied coil
- RMP – edge layer becomes fundamentally 3D
  - – a step toward stellarator !?
- Counter-intuitively, RMPs degrade particle confinement more than thermal
- RMP's have achieved some success in ELM suppression, but windows of operation limited. Understanding is poor.
- Alternatives : QH-mode, pellets, SMBI, …
- New Problem : SOL widths too narrow

→ Current Research Foci on Confinement Physics

- ‘Non-Locality’ and Transport in No Man’s Land

  → (microstability)

- Flow Physics : Zonal and Intrinsic Rotation

  → (quasi particles)

- L→H Transition : Dynamics, Thresholds

  → (quasi particles, neoclassical)

- Pedestal Modelling

- RMP, 3D Physics

  → (Hamiltonian chaos)

➔ Continuing impact of R.Z. Sagdeev in MFE world of 2013 indisputable.

## B.) A Recent Perspective : The Heat Flux 'Jamiton'

"On how the propagation of heat flux modulations triggers ExB flow pattern formation"

- Y. Kosuga, P.H. Diamond, O.D. Gurcan
  (PRL '13, in press)

"Transport of Radial Heat Flux and Second Sound in Fusion Plasmas"

- O.D. Gurcan, P.H. Diamond, X. Garbet, et al.
  (PoP '13, in press)

# Outline

- Motivation

- Extension of heat avalanche concept

- Relation to traffic flow problem

- Analysis

  → Instability calculation: suggestive of flux jam formation

  → maximal growth: comparison to staircase structure

- Implications for staircase and transport

- Summary

# Motivation

- ExB flows are important for tokamak confinement

  → Shear suppression of turbulent transport

- ExB flows are self-organized in tokamak plasmas

  → hierarchy of flow patterns:

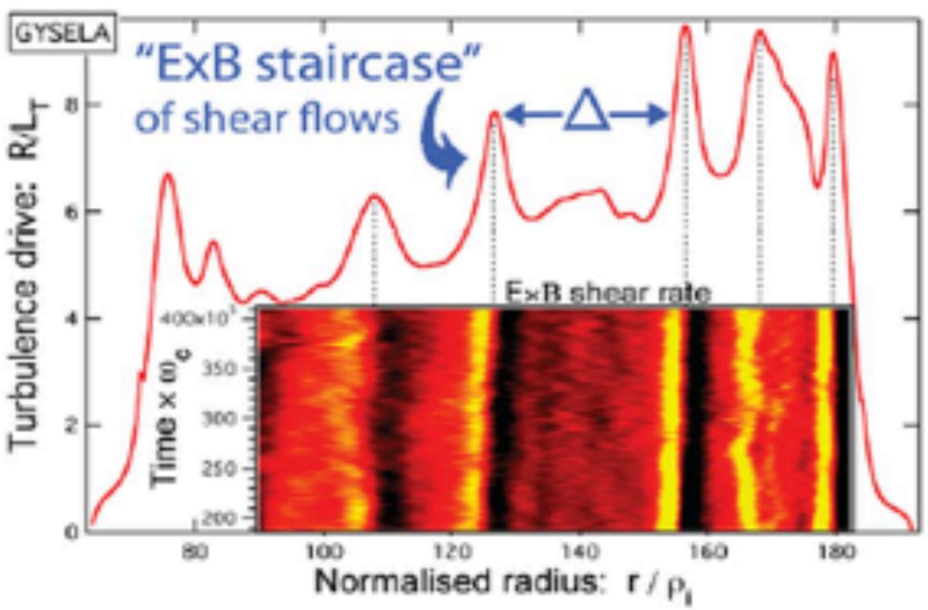
| Type of ExB flows | generation mechanisms |
|---|---|
| Mean ExB | transport bifurcation, strong mean gradients, mean shear flows |
| radially quasi-periodic zonal flows | drift wave turbulence, non-local energy transfer in k-space |
| ExB staircase | ????? |

see Sagdeev, et. al. ‘78

# What is the staircase?? → The Most Interesting Thing in GK Simulation in 10 years!

With G. Dif-Pradalier et. al.

## Analogy with geophysics: the '**E** × **B** *staircase*'





- Quasi-regular pattern of shear layer and profile corrugations

$$Q = -n\chi(r)\nabla T \quad \Rightarrow \quad \boxed{Q = -\int \kappa(r, r')\nabla T(r')\, dr'}$$

- '**E** × **B** staircase' width ≡ kernel width Δ
- coherent, persistent, jet-like pattern
  ⇒ the '**E** × **B** staircase'
- staircase NOT related to low order rationals!

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

# What is the staircase??

- The point:
  - fit: $Q = -\int dr' \kappa(r,r') \nabla T(r')$ $\quad \kappa(r,r') \sim \dfrac{S^2}{(r-r')^2 + \Delta^2}$ → some range in exponent
  - $\Delta >> \Delta_c$ i.e. $\Delta \sim$ Avalanche scale >> $\Delta_c$ ~ correlation scale
  - Staircase 'steps' separated by $\Delta$ ! → stochastic avalanches produce quasi-regular flow pattern!? → How?

    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 does system resolve pattern selection competition between zonal flow and streamer/ avalanche?

    → *spatial, domain decomposition, ala' spinodal decomposition?*

# Towards a model

- How do we understand quasi-regular pattern of ExB staircase, generated from stochastic heat avalanche???

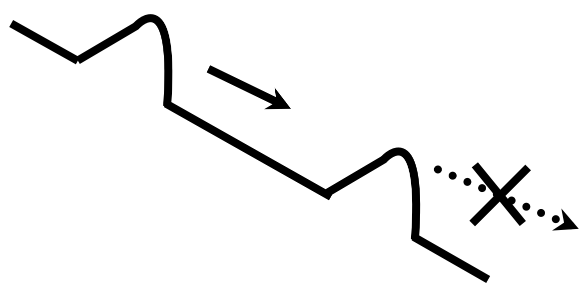
$\rightarrow$ 'eigenfunction' idea dubious, as no identifiable growth phase for staircase

- An idea: jam of heat avalanche

ExB staircase $\longleftrightarrow$ corrugated profile

$\rightarrow$ corrugation of profile occurs by 'jam' of heat avalanche flux

$\ast$ $\rightarrow$ time delay between $Q[\delta T]$ and $\delta T$ is crucial element



$\rightarrow$ accumulation of heat increment
$\rightarrow$ stationary corrugated profile

- How do we actually model heat avalanche 'jam' ??? $\rightarrow$ what is dynamical origin?

- $\delta T(x) \leftrightarrow v_E'$ via radial force balance $\Rightarrow$ onset

# Heat avalanche dynamics

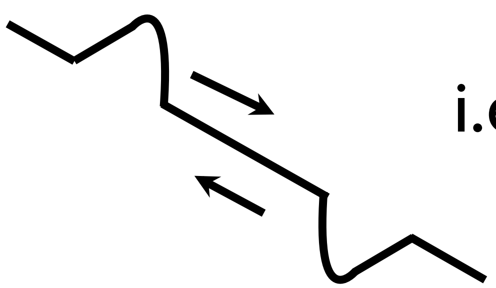
→ Hwa+Kardar ' 92, P.D. + Hahm ' 95, Carreras, et al. ' 96, ... GK simulation, ... Dif-Pradalier ' 10

- $\delta T$ :deviation from marginal profile → conserved order parameter

- Heat Balance Eq.: $\partial_t \delta T + \partial_x Q[\delta T] = 0$ → up to source and noise

- Heat Flux $Q[\delta T]$ ? – utilize symmetry argument, ala' Ginzberg-Landau

  - Usual: Diamond+Hahm ' 95 → ala joint reflectional symmetry (Hwa+Kardar)



i.e. blobs out, voids in

$$Q = Q_0(\delta T)$$
$$= \frac{\lambda}{2}\delta T^2 - \chi_2 \partial_x \delta T + \chi_4 \partial_x^3 \delta T$$

→ hyperdiffusion

lowest order → Burger' s equation $\partial_t \delta T + \lambda \delta T \partial_x \delta T = \chi_2 \partial_x^2 \delta T$

# An extension of the heat avalanche dynamics model

- An extension: allow a finite time relaxation of $Q$ toward SOC flux state

$$\partial_t Q = -\frac{1}{\tau}\left(Q - Q_0(\delta T)\right) \qquad Q_0[\delta T] = \frac{\lambda}{2}\delta T^2 - \chi_2 \partial_x \delta T + \chi_4 \partial_x^3 \delta T$$

Relaxation time: $\tau(\delta T, Q_0)$ lag between mean and instantaneous flux

i.e. $\tau$ enforces time delay between $\delta T$ and heat flux,
large near criticality

- Dynamics of heat avalanche:

$$\partial_t \delta T + \lambda \delta T \partial_x \delta T = \chi_2 \partial_x^2 \delta T - \chi_4 \partial_x^4 \delta T - \tau \partial_t^2 \delta T$$

$\partial_t \delta T + \lambda \delta T \partial_x \delta T$ → Burger's (P.D. + T.S.H. '95)

$\chi_4 \partial_x^4 \delta T$ → Hyper-diffusion

$\tau \partial_t^2 \delta T$ → New: due finite response time

→ Instability, 'Flux jamiton'

→ heat equation

→ Burgers Eqn.

→ Wave Eqn.

→ Collective Dynamics of Turbulent Eddy
'Aether' I – First Quasi-Particle Model of Transport?!

– Kelvin, 1887

XLV. *On the Propagation of Laminar Motion through a turbulently moving Inviscid Liquid. By* Sir WILLIAM THOMSON, *LL.D., F.R.S.**

1. IN endeavouring to investigate turbulent motion of water between two fixed planes, for a promised communication to Section A of the British Association at its coming Meeting in Manchester, I have found something seemingly towards a solution (many times tried for within the last twenty years) of the problem to construct, by giving vortex motion to an incompressible inviscid fluid, a medium which shall transmit waves of laminar motion as the luminiferous æther transmits waves of light.

2. Let the fluid be unbounded on all sides, and let $u$, $v$, $w$ be the velocity-components, and $p$ the pressure at $(x, y, z, t)$. We have

$$\frac{du}{dx}+\frac{dv}{dy}+\frac{dw}{dz}=0 \quad . \quad . \quad . \quad . \quad . \quad (1),$$

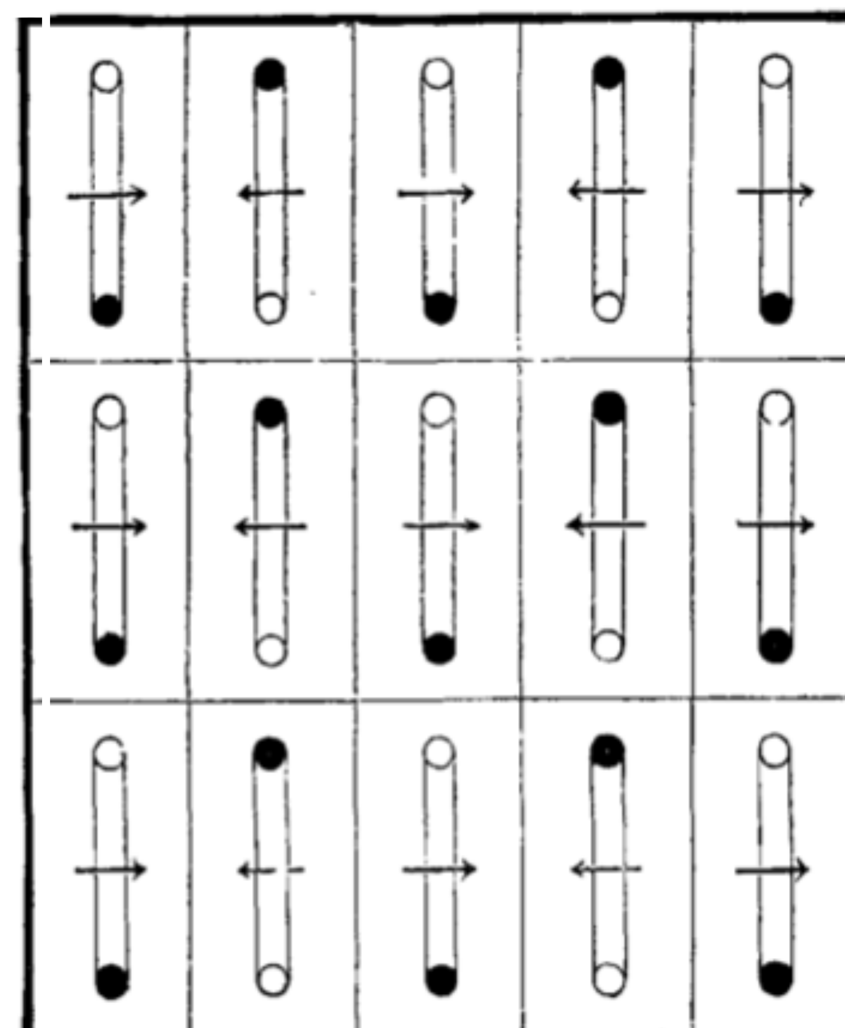
* Communicated by the Author, having been read before Section A of the British Association at its recent Meeting in Manchester.

21. Eliminating the first member from this equation, by (34), we find

$$\frac{d^2 f}{dt^2} = \tfrac{2}{9} R^2 \frac{d^2 f}{dy^2} \quad . \quad . \quad . \quad . \quad . \quad . \quad (51).$$

Thus we have the very remarkable result that laminar disturbance is propagated according to the well-known mode of waves of distortion in a homogeneous elastic solid ; and that the velocity of propagation is $\frac{\sqrt{2}}{3}$R, or about ·47 of the average velocity of the turbulent motion of the fluid.

Fig. 1.



→ time delay between Reynolds stress and wave shear introduced

→ converts diffusion equation to wave equation

→ describes wave in ensemble of vortex quasi-particles

– c.f. "Worlds of Flow", O. Darrigol

# Relaxation time - the idea

- What is '$\tau$'? → Analogy from traffic jam dynamics

  → c.f. Whitham!

- A useful analogy:

| avalanche dynamics | traffic flow dynamics |
|---|---|
| temp. deviation from marginal profile | local car density |
| heat flux | traffic flow |
| mean SOC flux (ala joint reflection symmetry) | equilibrium, steady traffic flow $V(\rho)$ |
| heat flux relaxation time $\tau$ | driver's reaction time $\tau$ |

→ driver's response can induce jam

→ jam in avalanche → profile corrugation → staircase?!?

→ key distinction: instantaneous flux vs. mean flux

# Excitons in Traffic: The 'jamiton'

- A model for Traffic jam dynamics → Whitham

$$\rho_t + (\rho v)_x = 0$$

$$v_t + v v_x = -\frac{1}{\tau}\left\{ v - V(\rho) + \frac{\nu}{\rho}\rho_x \right\}$$

$\rho$ → car density

$v$ → traffic flow velocity

$V(\rho) - \frac{\nu}{\rho}\rho_x$ → an equilibrium traffic flow

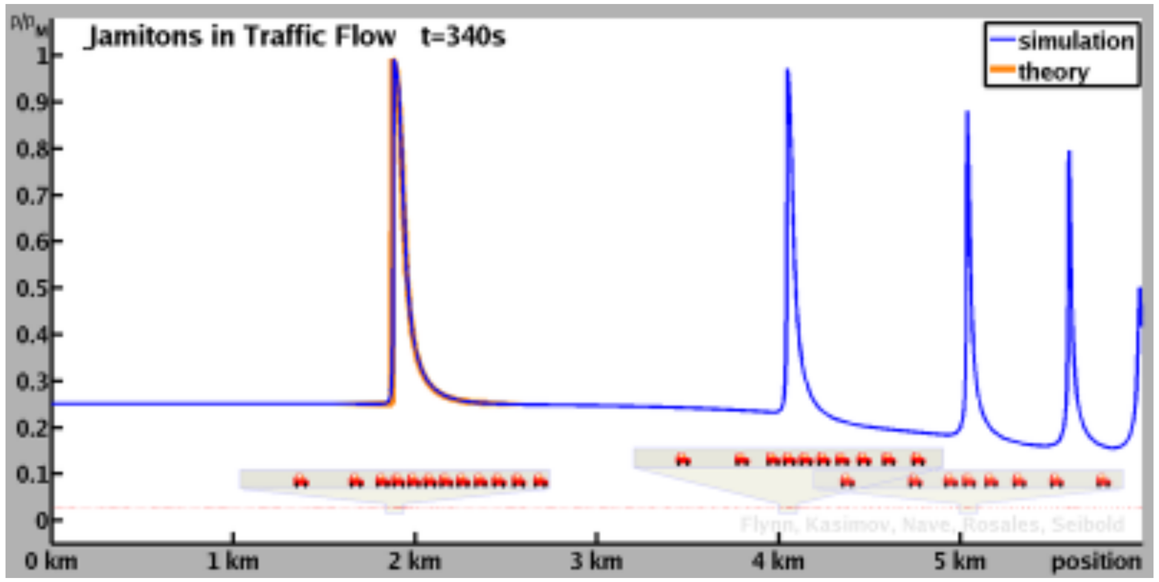
$\tau$ → driver's response time

→ Instability occurs when $\tau > \nu/(\rho_0^2 V_0'^2)$

$D_{eff} = \nu - \tau \rho_0^2 V_0'^2 < 0$ → clustering instability

→ Indicative of jam formation

- Simulation of traffic jam formation



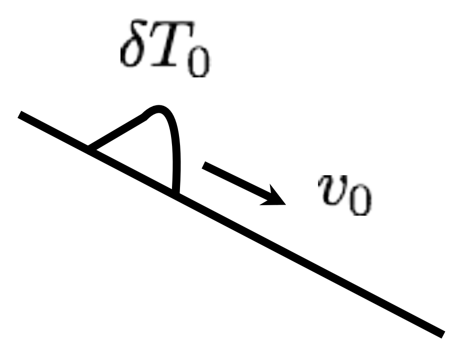

http://math.mit.edu/projects/traffic/

→ Jamitons (Flynn, et.al., '08)

n.b. : I.V.P. → decay study

# Analysis of heat avalanche dynamics: 1

- How do heat avalanches jam?




- Consider an initial avalanche,
  with amplitude $\delta T_0$,
  propagating at the speed $v_0 = \lambda \delta T_0$

- negative heat conduction instability occurs if $v_0^2 \tau$ (related to streaming) beats $\chi_2$ => overshooting => clustering, as Q can depart $Q_0(\delta T)$

$$\partial_t \widetilde{\delta T} + v_0 \partial_x \widetilde{\delta T} = \chi_2 \partial_x^2 \widetilde{\delta T} - \chi_4 \partial_x^4 \widetilde{\delta T} - \tau \partial_t^2 \widetilde{\delta T}$$

$$\rightarrow (\chi_2 - v_0^2 \tau) \partial_x^2 \widetilde{\delta T} - \chi_4 \partial_x^4 \widetilde{\delta T}$$ ; in moving frame of avalanche

n.b. akin to negative viscosity instability

→ Recall ZF as secondary mode in the gas of primary DW

→ Heat flux 'jamiton' as secondary mode in the gas of primary avalanches

→ More generally, both are examples of 'second sound', as in phonon gas

# Analysis of heat avalanche dynamics: 2

- Growth rate of the pulse: $\rightarrow$ negative heat conduction instability

$$\gamma = -\frac{1}{2\tau} + \frac{1}{2\tau}\sqrt{\frac{r+1}{2} - 2\tau\chi_2 k^2\left(1+\frac{\chi_4 k^2}{\chi_2}\right)} \qquad r = \sqrt{\left\{4\tau\chi_2 k^2\left(1+\frac{\chi_4 k^2}{\chi_2}\right)-1\right\}^2 + 16 v_0^2 k^2 \tau^2}$$

- Threshold for instability: $\tau > \frac{\chi_2}{v_0^2}\left(1+\frac{\chi_4 k^2}{\chi_2}\right)$

but $1/\tau = 1/\tau[\mathcal{E}]$

clustering instability strongest near criticality

- Scale for maximum growth (assuming $k^2 < \frac{\chi_2}{\chi_4}$, scale not so small that $\chi_4$ dominates)

$$k^2 \cong \frac{\chi_2}{\chi_4}\sqrt{\frac{\chi_4 v_0^2}{4\chi_2^3}} \quad \text{from} \quad \frac{\partial\gamma}{\partial k^2} = 0 \quad \Rightarrow \quad 8\tau\frac{\chi_4^2}{\chi_2}k^6 + 4\tau\chi_4 k^4 + 2\frac{\chi_4}{\chi_2}k^2 + 1 - \frac{v_0^2\tau}{\chi_2} = 0$$

$\rightarrow$ staircase size $\Delta^2_{stair}(\delta T)$, $\delta T$ from saturation $\longleftrightarrow$ consider shearing!

# Analysis of heat avalanche dynamics: 3

- Saturation: shearing strength to kill clustering instability

avalanche growth → profile corrugation → ExB staircase → $v'_{E\times B}$

$v'_{E\times B} \sim \gamma_{max}$ (feedback to avalanche growth)

→ guesstimate, only → onset, only, of step formation

- Saturated amplitude: $\frac{\delta T}{T_i} \sim \frac{1}{v_{thi}\rho_i}\sqrt{\frac{\chi_4}{\tau}}$

from $\gamma_{max} \cong \frac{1}{2\tau}\sqrt{\frac{v_0^2\tau}{\chi_2}} \sim \frac{\lambda T_i}{2\sqrt{\chi_2\tau}}\frac{\delta T}{T_i}$ and $v'_{E\times B} \cong \frac{c}{eB}\delta T'' \sim \omega_{ci}\rho_i^2 k_{max}^2\frac{\delta T}{T_i} \sim \omega_{ci}\frac{\rho_i^2\lambda T_i}{2\sqrt{\chi_2\chi_4}}\left(\frac{\delta T}{T_i}\right)^2$

→ Radial Force Balance

- Staircase width: $\Delta_{stair}^2 \sim k_{max}^{-2}(\delta T) \sim \frac{2v_{thi}}{\lambda T_i}\rho_i\sqrt{\chi_2\tau}$ $\chi_2 \sim \chi_{neo}$

→ Geometric mean of $\rho_i$ and $\sqrt{\chi_2\tau}$

→ neoclassical diffusion length in 1 relaxation time

→ 'standard' numbers: $\Delta_{stair} \sim 10\Delta_c$

# Toward Systematics (1):

- to evolve $\mathcal{T}$ self-consistently, need $\partial_t \mathcal{E}$ eqn. for $1/\tau[\mathcal{E}]$

  → Turbulence intensity evolution

- Feedback system for $\delta T$ and $\mathcal{E}$ , with Q as control parameter

- Key idea: $\mathcal{T}$ long, near marginal

- $Q = -\chi \nabla T$ replaced by

$$\tau \partial_t Q + Q + \chi_T \nabla T + \text{heat flux scattering} = S_0$$

akin intensity equation for $Q$ ⟷ c.f. turbulence spreading

# Toward Systematics (2):

- can 'derive' $\partial_t Q$ eqn.

  (extended Guyer-Krumhansl relation, relevant to transport in phonon gas)

  from moments of: $\partial_t \langle \delta f^2 \rangle$ → 2pt correlation evolution

  → c.f. O.D.G, P.D., Garbet, et. al.

- re-enforces point that 2pt correlation evolution is FUNDAMENTAL. Those Space fluxes are production there.

- for experiment: need separate $Q$ from $\nabla \langle T \rangle$, with high resolution!

  i.e. severe challenge

# A Glimpse at Some Results

- 2pt correlation evolution

$$\left(\frac{\partial}{\partial t}+\mathcal{L}_1+\mathcal{L}_2\right)\langle\tilde{f}_1\tilde{f}_2\rangle+\mathcal{P}_1\bar{f}_1+\mathcal{P}_2\bar{f}_2=\nabla_1\cdot\Gamma_{Q_1}+\nabla_2\cdot\Gamma_{Q_2}+\partial_{v_{\parallel 1}}\mathcal{K}_1+\partial_{v_{\parallel 2}}\mathcal{K}_2$$

$$\mathcal{L}_{1,2}=v_{\parallel 1,2}\nabla_{\parallel 1,2}+\frac{q}{m}\bar{E}_{\parallel 1,2}\frac{\partial}{\partial v_{\parallel 1,2}} \qquad \mathcal{P}_{1,2}=\langle\tilde{f}_{1,2}\tilde{\mathbf{v}}_{E1,2}\rangle\cdot\nabla_{1,2}+\frac{q}{m}\langle\tilde{f}_{1,2}\tilde{E}_{\parallel 1,2}\rangle\frac{\partial}{\partial v_{\parallel 1,2}}$$

$$\Gamma_{Q_{1,2}}=\langle\tilde{\mathbf{v}}_{E1,2}\tilde{f}_1\tilde{f}_2\rangle \qquad \mathcal{K}_{1,2}=\langle\tilde{E}_{\parallel 1,2}\tilde{f}_1\tilde{f}_2\rangle$$

- Energy moment → Guyer-Krumhansl Structure

↓

$$\partial_t Q-\partial_x(D_x(\mathcal{E})\partial_x Q)=-D_y(\mathcal{E})k_y^2(Q-\chi(\mathcal{E})\partial_x\langle T\rangle)$$

➔ couples relaxation to heat flux scattering

↓ spreading

↓ turbulent poloidal decorrelation

↘ mean turbulent heat flux

# Summary

- A model for ExB staircase formation

Heat avalanche → Profile corrugation → ExB staircase

Profile corrugation due to 'jam' of heat flux avalanche!

Key:

- Analysis of heat flux jam dynamics

→ clustering instability when plasma response time is long

$$\gamma = -\frac{1}{2\tau} + \frac{1}{2\tau}\sqrt{\frac{\tau+1}{2} - 2\tau\chi_2 k^2\left(1+\frac{\chi_4 k^2}{\chi_2}\right)} \qquad \tau > \frac{\chi_2}{v_0^2}\left(1+\frac{\chi_4 k^2}{\chi_2}\right)$$

→ length scale of most jamming unstable modes → step size

$$\Delta^2_{stair} \sim k^{-2}_{max}(\delta T) \sim \frac{2v_{thi}}{\lambda T_i}\rho_i\sqrt{\chi_2\tau}$$

## Summary

More importantly, new perspective on:

- SOC and relaxation

- Shear flow formation

- Formulation of heat transport and spreading

C.) Looking Ahead

→ MFE confinement theory evolves and continues

to be a dynamic research field

→ a recent success study : intrinsic rotation

- discovered in ‘95 (Ida), ‘97 (Rice)
- extensively investigated by theory and simulation 2005 –
- now entering maturity …

➔ simulation, especially GK, increasingly central but need diversify simulation models, approaches

→ ITER issue

- need a change in concept:
  - → '60 – now: design for optimal confinement
  - → now – ITER, DEMO: design for optimal power handling
- corollary: Is the H-mode the way to go?

  n.b. : really seek optimal energy, not particle, confinement
- a possibility: I-mode (c.f. AUG, Alcator C-Mod, …)
  - H-mode energy confinement with L-mode particle confinement
  - sub-critical to transitions but strong zonal mode activity
  - much to learn …

➔ R. Z. Sagdeev's impact on MFE physics, initiated in early 60's, is strong and visible in 2013