

#### Turbulent transport in magnetised plasmas Xavier Garbet

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# Turbulent transport in magnetised plasmas

#### Xavier Garbet IRFM CEA Cadarache

#### **Turbulent transport: why?**

- Turbulent transport degrades confinement in magnetic fusion devices
- Would like to improve confinement → transport barriers
- Plays an important role in astrophysics and geophysics



#### Nested magnetic surfaces

#### **Turbulent transport: why?**

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#### **Outline**

- Turbulent transport : an introduction
- Fluxes vs gradients and thermodynamics
- Building transport barriers
- Turbulence self-regulation : when instability threshold matters



### **Turbulence is driven by micro-instabilities**

Driven by gradients → instability threshold Kadomtsev 66, Coppi 67, Horton 81, Rewoldt 87, Romanelli 89

• Family of drift-waves - interchange  $\nabla P \cdot \nabla B > 0$  usually prevails.



X. Garbet, Alfvén prize talk, 48th EPS conference, June, 27 2022

#### What does it look like?



Grandgirard GYSELA-X 2020

# **Building a transport model**



PAGE 8

# **Building a transport model**

- Power law decay , frequency spectra are broad Hennequin 04,09, Mazzucato 08,09
- Amplitude ~mixing-length theory Prandtl 1905

$$\frac{\delta n}{n} \sim \frac{\ell_c}{L_n}$$

$$\rightarrow \text{ yields diffusion vs gradients}$$

$$D \sim \frac{\ell_c^2}{\tau_c}$$

$$\rightarrow \text{ reduced transport models}$$

Staebler 07, Bourdelle 16



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#### Issues

- Up-gradient transport is ubiquitous consistency with second principle?
- Can turbulent transport be controlled?
- Scale separation may not hold: interaction between small and large scales mediated by mesoscale turbulent structures.

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#### **Transport equations bear a puzzling shape**

Evolution of density, velocity, temperature A = (N,V//,T)

$$\frac{\partial A}{\partial t} + \nabla \cdot \Gamma = \Sigma \qquad \Gamma = \overline{L} \cdot A' + \Gamma_{res}$$

- Transport matrix  $\overline{L}$  is symmetric Onsager 1931. Unexpected:
- "residual" stress and heat flux  $\Gamma_{
  m res}$
- turbulent heating and acceleration  $\Sigma$  Rudakov 71, Ott 72



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PAGE 13

# Wave transport is responsible for residual fluxes

- Total field + particle momentum/energy is conserved → extended thermodynamics Boozer 92, Krommes 93, Sugama 96, Watanabe 06, XG 13
- Residual = fluxes of momentum/ energy carried by waves.
- Requires symmetry breaking Peeters 07, Gürcan 07, Diamond 08, Camenen 09 e.g. mean shear flow



#### **Turbulence produces momentum** and heat sources

• Source terms Itoh 88, Hinton 06, Barnes 12, Lu Wang 13, XG 13, Seiferling 18, Wang 18

$$\Sigma_{V_{\parallel}} = \langle neE_{\parallel} \rangle$$
$$\Sigma_{T} = \langle \boldsymbol{J} \cdot \boldsymbol{E} \rangle$$

- Correlation requires symmetry breaking
- Charge conservation  $\rightarrow$ transfer Waltz 11. Wave energy transport  $\rightarrow$  net effect Zhao 12



Waltz 08

# Turbulent pinch theory successfully tested in tokamaks

- Particle flux  $\Gamma = -D \frac{dn}{dr} + \mathcal{V}n$
- "Pinch velocity" V due to temperature and velocity gradients, and compressibility Angioni 03 & 06, XG 04, Camenen 09
- Entropy production rate > 0 XG05.
- Onsager symmetry → thermal pinch Dominguez 89, Luce 92, Itoh 96, Mantica 05, Lu Wang 11



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Luce 95 – DIII-D



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PAGE 17

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# Mean shear flow reduces turbulent transport

Mean shear flow → vortex distortion, size reduction.
 Shear flow rate

$$\omega_E = \frac{dV_E}{dr}$$

- Reduction of correlation length → diffusivity is reduced
- Turbulence quench Biglari 90, Waltz 95, Hahm 95

$$\omega_E > \gamma_{max}$$



# Evidence of shear flow driven transport barriers



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PAGE 20

## **Controlling shear flows**

Radial electric field

controlled by radial currents

Itoh 88, Kobayashi 20

$$\epsilon_{pol} \frac{\partial E_r}{\partial t} = -\sum J_r$$

 Many contributions: viscous damping, Reynolds stress, orbit losses, wave momentum transport, neutrals → power threshold

#### • Mean shear flow only? Burrell 99, Gohil 11, Ryter 13, Viezzer 13, Schmitz 12, Tynan 13





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# Magnetic perturbations is one way to control mean flows

**Becoulet 22** 

 Ergodic field lines degrade confinement: E<sub>r</sub> w/o RMP shear weaker Schmitz 19, Becoulet 22, + less zonal flow generation Chen 20 Non resonant 3D field perturbations enhance E<sub>r</sub> with **RMP** Varennes 22 + effect on stability Huang 22. Can be optimised Park 21

-20 -20 -20 -20 -20 -40 -60 -7.6e+01



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#### **Turbulence drives zonal flows**

#### Zonal Flows generated by

turbulence Sagdeev 78, Hasegawa 79, Lin 98, Diamond 05

• Similar to jet streams in rotating fluids Roberts 68, Busse 70

[GYSELA, 2018] r 0.012 0.010 0.008 0.006 0.004 0.002 A 0.000 -0.002

Zonal Flows in tokamak plasma

# Zonal flows back react on turbulence via wave scattering from large to small scales



| PAGE 27

#### **Avalanches enhance transport**

• Avalanches: large scale transport events Diamond 95, Carreras 96, Sarazin

98, XG 98, Beyer 02, Sanchez 15

#### • Propagating fronts

Hahm 04, Gurcan 05, XG07, Idomura 09, McMillan 09, Villard 19



#### **Avalanches enhance transport**

r

#### Heat diffusivity vs radius and time



#### Idomura 09 GT5D



#### Avalanches: large

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#### Propagating fronts

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#### **Turbulence self-organises near threshold**

Dif-Pradalier 17

- Staircase patterns

   observed in turbulence
   simulations Dif-Pradalier
   15&17, Rath 16, Weikl 18, Wang
   18, Qi 19, Ivanov 20.
- Consistent with

observations Hornung 16, Choi 20, Qi 21.



# • Staircase : avalanching areas bounded by zonal shear layers Kosuga 14, Ashourvan 16, 17, Wang 18, Guo 19, XG21

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Salt fingers in thermocline of the tropical atlantic Schmitt Science 05

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### **Turbulence spreads**

- 2 mechanisms xG 94,96:
- wave group velocity Kishimoto 96,99
- front propagation Diamond-Hahm 95, Gürcan 05, Zonca 05, XG07
- Range of spreading depends on damping.
   Related to avalanches Idomura 09, McMillan 09



# Interplay of edge with core turbulence

- Immersive boundary conditions  $\rightarrow$  limiter
- Produces turbulence, propagates inward
- Back-reacts on far edge turbulence.

→ turbulence fills-in linearly stable edge region



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#### Dif-Pradalier 2022



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Dif-Pradalier 2022



#### Conclusion

- A lot has been understood key is self-organisation via flows
- Some outstanding issues:
- interplay edge/core turbulence (see plenary S. Krasheninnikov)
- electromagnetic effects (see plenary J. Garcia), link with MHD
- interplay with collisional transport, 3D magnetic perturbations