Gyrokinetic Turbulence in Laboratory and Astrophysical Plasmas

Max-Planck-Institut für Plasmaphysik, Garching
Universität Ulm

ASTRONUM 2009
Chamonix, France, 29 June 2009
Many thanks to…

My co-workers at Garching:
F. Merz, M.J. Püschel, T. Görler, T. Hauff, K. Reuter,
D. Told, M. Schneller, A. Röder, H. Doerk-Bendig

My co-workers at Münster University:
R. Friedrich, H. Angenent, J. Hüser, M. Wilczek

Various other collaboration partners at:
Germany (Munich, Greifswald, Göttingen, Chemnitz etc.)
Europe (Brussels, Lausanne, Oxford, Gothenburg etc.)
USA (Princeton, Maryland, Madison, Livermore etc.)
Japan (National Institute for Fusion Science etc.)

www.ipp.mpg.de/~fsj
Research topics

- Plasma astrophysics (incl. dynamo physics)
- Turbulence in magnetized plasmas
  - Code development
  - Basic physics issues
  - Applications to experiments
- Colloidal (dusty) plasmas
- Computational fluid dynamics
- Computational plasma physics
- Non-Gaussian diffusion in complex systems

www.ipp.mpg.de/~fsj
Computer simulations (Virtual experiments)

Gene (kinetic continuum code)
XGC-0 (kinetic PIC code)
DPS (molecular dynamics code)
DYNAMO (nonlinear MHD code)
TURB3D (nonlinear fluid code)
etc.

Experiments or observations
Fusion experiments (AUG, JET etc.)
Smaller lab experiments
Astrophysical data
etc.

Analytical theories
Kinetic theory
Nonequilibrium statistics
Nonlinear dynamics
Closure theories
etc.
Plasma turbulence
Plasma turbulence in astrophysics and in the laboratory

Key issues: Turbulent transport, Anomalous heating/dissipation
Fusion energy in the stars

This points the way to a CO$_2$ free energy source for the 21$^{st}$ century…
Deuterium-Tritium fusion has by far the highest probability under experimentally accessible conditions.

Still, temperatures of about 100 million degrees are required! Thus, we are dealing with a fully ionized gas (plasma).

Two main approaches: Inertial fusion and magnetic fusion.
ITER and plasma turbulence

ITER is an extremely challenging scientific project, aimed at investigating burning D-T plasmas.

It is currently being built in Cadarache.

The success of ITER depends on our understanding of plasma turbulence.

www.iter.org
Plasma turbulence: GENE simulations

www.ipp.mpg.de/~fsj/gene
Key idea: Applications of insights, theories, and tools to astrophysics

Some issues under investigation:

• Role of microturbulence in astrophysics?

• How does MHD turbulence dissipate energy?

• How do fast particles interact with turbulence?
Gyrokinetic turbulence
What is gyrokinetic theory?

Dilute and/or hot plasmas are almost collisionless. Thus, if kinetic effects (finite Larmor radius, Landau damping, magnetic trapping etc.) play a role, MHD is not applicable, and one has to use a (reduced) kinetic description!

Vlasov-Maxwell equations

\[ \frac{\partial}{\partial t} + \mathbf{v} \cdot \frac{\partial}{\partial \mathbf{x}} + \frac{q}{m} \left( \mathbf{E} + \frac{\mathbf{v}}{c} \times \mathbf{B} \right) \cdot \frac{\partial}{\partial \mathbf{v}} f(\mathbf{x}, \mathbf{v}, t) = 0 \]

Removing the fast gyromotion

(gyrokinetic ordering of scales / amplitudes)

\[ \omega \ll \Omega \]

[Frieman, Chen, Lee, Hahm, Brizard et al., 1980s]

Charged rings as quasiparticles; gyrocenter coordinates; keep FLR effects

Brizard & Hahm, Rev. Mod. Phys. 79, 421 (2007)
The nonlinear gyrokinetic equations

\[ f = f(X, v_\parallel, \mu; t) \]

Advection/Conservation equation

\[ \frac{\partial f}{\partial t} + \dot{X} \cdot \frac{\partial f}{\partial X} + v_\parallel \frac{\partial f}{\partial v_\parallel} = 0 \]

\[ \dot{X} = v_\parallel b + \frac{B}{B_\parallel^*} \left( \frac{v_\parallel}{B} \bar{B}_1\perp + v_\perp \right) \]

\[ v_\perp = \frac{c}{B^2} \bar{E}_1 \times B + \frac{\mu}{m\Omega} b \times \nabla (B + \bar{B}_1\parallel) + \frac{v_\parallel^2}{\Omega} (\nabla \times b)_\perp \]

\[ \dot{v}_\parallel = \frac{\dot{X}}{mv_\parallel} \cdot \left( e\bar{E}_1 - \mu \nabla (B + \bar{B}_1\parallel) \right) \]

\[ \frac{B_1\parallel}{B} = - \sum \epsilon_\beta \left( \frac{B_1\perp}{n_0 T} + ||xI_1I_0|| \frac{e\phi_1}{T} + ||x^2I_1^2|| \frac{B_1\parallel}{B} \right) \]

\[ \frac{n_1}{n_0} = \frac{\bar{n}_1}{n_0} - \left( 1 - ||I_0^2|| \right) \frac{e\phi_1}{T} + ||xI_0I_1|| \frac{B_1\parallel}{B} \]

\[ \nabla_\perp^2 A_1\parallel = -\frac{4\pi c}{c} \sum J_1\parallel \]

Nonlinear integro-differential equations in 5 dimensions...
Gradient-driven microinstabilities

Drive (transport) range dynamics is not universal.

Microinstabilities have perpendicular wavelengths of several ion/electron gyroradii.
Anisotropy of turbulent fluctuations

Strong background magnetic field causes turbulence to be quasi-2D

Possible simulation volume: flux tube, annulus, full (or fractional) torus
Turbulent mixing in a tokamak

ExB drift velocity

\[ \vec{v}_{EB} = \frac{e}{B^2} \vec{B} \times \nabla \phi \]

\[ Q \equiv \frac{3}{2} \langle \vec{p} \cdot \vec{v}_{EB} \rangle = -n \chi \nabla T \]

\[ \chi \sim \frac{(\delta x)^2}{\delta t} \sim \frac{n^2 v_k}{L_IT} \]

(random walk/mixing length estimates)

Typical heat and particle diffusivities are of the order of 1 m²/s.
Major theoretical speedups

relative to original Vlasov/pre-Maxwell system on a naïve grid, for ITER $1/\rho_* = a/\rho \sim 1000$

- Nonlinear gyrokinetic equations
  - eliminate plasma frequency: $\omega_{pe}/\Omega_i \sim m_i/m_e \quad x10^3$
  - eliminate Debye length scale: $(\rho_i/\lambda_{De})^3 \sim (m_i/m_e)^{3/2} \quad x10^5$
  - average over fast ion gyration: $\Omega_i/\omega \sim 1/\rho_* \quad x10^3$

- Field-aligned coordinates
  - adapt to elongated structure of turbulent eddies: $\Delta_///\Delta_\perp \sim 1/\rho_* \quad x10^3$

- Reduced simulation volume
  - reduce toroidal mode numbers (i.e., 1/15 of toroidal direction) $x15$
  - $L_r \sim a/6 \sim 160 \rho \sim 10$ correlation lengths $x6$

- **Total speedup** $x10^{16}$

- For comparison: Massively parallel computers (1984-2009) $x10^7$
The simulation code GENE

- GENE is a **physically comprehensive and well benchmarked** code

- GENE is **publicly available** ([www.ipp.mpg.de/~fsj/gene](http://www.ipp.mpg.de/~fsj/gene))

- various applications in **fusion research** (tokamaks and stellarators) and **astrophysics**; can be run as a (radially) **local or global** code

- the differential operators are discretized via a combination of **spectral, finite difference, and finite volume methods**; the time stepping is done via a (non-standard) **4th-order explicit Runge-Kutta method**

- in addition, GENE can also be run as a **linear eigenvalue solver**

- two main goals: **deeper understanding of fundamental physics issues and direct comparisons with experiments** (interfaces to MHD codes)
GENE is a massively parallel code

- Parallelization due to high-dimensional domain decomposition (either pure MPI or mixed MPI/OpenMP paradigm)
- GENE runs very efficiently on a large number of parallel platforms (including IBM BlueGene, IBM Power6, Cray XT4, SGI Altix etc.)
- GENE is part of the European DEISA benchmark suite and the EU-Japanese IFERC benchmark suite
GENE on BlueGene/L (strong scaling)

(number of processors)

(Speedup: 14.2 / 16)

(problem size: ~300-500 GB; measurements in co-processor mode at IBM Watson Research Center)
Role of microturbulence in astrophysics?
Broad-line regions in AGNs

Measured electromagnetic spectra from AGNs suggest the existence of...

...cold, dense clouds in a hot, dilute, magnetized medium in the central region of AGNs.

How can those cold clouds survive?

Standard model (e.g. Kuncic et al., MNRAS 1996):
Cold clouds are magnetically confined and form filaments; perpendicular transport is negligible.

What if microturbulence is taken into account?
Microturbulence effects?

∇T ≠ 0, ∇n ≠ 0, magnetic confinement
⇒ evaporating clouds prone to plasma microinstabilities

Taking typical parameters (e.g., Kuncic 1996):

\( n_{\text{cloud}} \sim 10^{17} \text{ cm}^{-3}, \ T_{\text{medium}} \sim 10^9 \text{ K} \) and assuming gyrokinetic transport (ITG) levels:

\[
 t_{\text{evap}}^{\text{GK}} \sim 10^{9-10} \text{ s}
\]

- significantly larger than unhindered evaporation
- however: too large for the standard model?

More detailed investigations are currently underway.
How does MHD turbulence dissipate energy?
Turbulence as a **local cascade in wave number space**…

\[ E(k) = C \varepsilon^{2/3} k^{-5/3} \]

**K41 theory**

„Big whorls have little whorls, little whorls have smaller whorls that feed on their velocity, and so on to viscosity“

The Richardson cascade is a nonlinear route to dissipation.
Solar wind turbulence: Dissipation?

Collisionless damping of (shear) Alfvén waves
Dannert & Jenko, CPC 2004

High-k MHD turbulence satisfies the gyrokinetic ordering!

Bale et al., PRL 2005
High-k Alfvén wave turbulence: Observations versus simulations

AW turbulence in the solar wind
Bale et al., PRL 2005

GK simulation of AW turbulence
Howes et al., PRL 2008
How do fast particles interact with turbulence?
Diffusivities and correlations

Test particle approach

- Diffusion equation: $\partial_t n(x, t) = D(t) \nabla^2 n(x, t)$

- Einstein (1905): $D_x(t) = \frac{1}{2} \frac{d}{dt} \langle \delta x^2(t) \rangle$

- Taylor (1920): $D_x(t) = \frac{1}{2} \frac{d}{dt} \langle \delta x^2(t) \rangle = \int_0^t d\xi \langle v_x(0) v_x(\xi) \rangle \equiv \int_0^t d\xi L_{v_x}(\xi)$
Validity of gyro/orbit averaging

\[ \Xi_{o.a.} = \max\{V_E, |v_{dr} - v_y|\} \frac{T_{\text{orbit}}}{\lambda_c} < 1, \quad T_{\text{orbit}} \ll \tau_c \]

Magnetic transport along fluctuating field lines: \[ v_B \equiv \dot{v}_\parallel (\hat{B}_r/B_0). \]
Scaling laws: Diffusivities vs energy

Analytical theory is confirmed by GENE simulations

Magnetic transport of beam ions is independent of energy!

Hauff et al., PRL 2009
Cosmic rays in astrophysical turbulence

Example: Solar wind

(other candidates: interstellar medium, intergalactic medium, jets etc.)

Cross-field transport:
• Gyro averaging is not valid for highly energetic particles
• Particle diffusivity may clearly exceed naïve estimates
Conclusions
Some key points of this talk

Fusion-oriented plasma physics has developed sophisticated theories / tools, some of which can be applied to astrophysics.

Questions under investigation (partial list):

- Role of microturbulence in astrophysics?
- How does MHD turbulence dissipate energy?
- How do fast particles interact with turbulence?
- Kinetic effects in the magnetorotational instability?
- Heating of the solar corona?

Collaborative efforts are underway (e.g. MPI for Solar Systems Research & MPI for Plasma Physics)