Waves and turbulence in the solar wind

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PG Lectures

- Turbulence: the basics
- Turbulence in plasmas: MHD scales
- The solar wind context
- Open questions
What is turbulence?

- Fluid phenomenon
- Nonlinear energy transfer between scales
- Occurs when inertial forces dominate viscous forces
- Important in many engineering problems
Early Concepts

• “… the motion of the surface of the water … has eddying motions, one part of which is due to the principal current, the other to random and reverse motion”

    → Reynolds decomposition:
    \[ u = u_0 + \delta u \]

• “large things are rotated only by large eddies and not by small ones, and small things are turned by both small eddies and large”

    → Cascade of eddies

da Vinci 1510
The Richardson cascade

Bigger whirls have little whirls,  
That feed on their velocity;  
And little whirls have lesser whirls,  
And so on to viscosity.

Lewis Fry Richardson, 1920
The inertial range

- If energy input is steady, and far from dissipation scale, have a steady state → **Inertial range**

- K41: $k^{-5/3}$ spectrum

- We observe this in hydrodynamic fluids

- Note: energy transfer rate is analytic in hydrodynamics
Measuring the Power Spectrum

- Taylor (1938)
  - if bulk flow is faster than turbulent motions
  - can measure velocity at fixed point
  - measured time variations correspond to spatial variations in the flow

Fukushima & Westerweel 2007

McComb 1995 RPP
Turbulence in plasmas

Neutral fluids
- Motion described by Navier-Stokes equations
  → Hydrodynamics
- Energy transfer by velocity shear

Plasmas
- On sufficiently large scales, can treat plasma as a fluid
  → Magnetohydrodynamics
- Multiple, finite amplitude waves can be stable
- Presence of a magnetic field
  - Breaks isotropy
  - Key difference to neutral fluids
“The great power law in the sky”

- Measure interstellar density fluctuations using scintillations
- Consistent with Kolmogorov scaling over many orders of magnitude
Why study waves and turbulence in the solar wind?

Effect on the Earth
- Can trigger reconnection, substorms, aurorae, …

Understanding solar processes
- Signature of coronal heating, etc.

Application to other plasmas
- Astrophysics: particle propagation
- Dense plasmas: transport

Turbulence as a universal phenomenon
- Comparison with hydrodynamics
Cosmic rays and the solar cycle

- Cosmic ray flux at the Earth is modulated by the solar cycle
- This is due to variations in the magnetic barrier in the solar system
- Waves and turbulence in the solar wind form a key part of this barrier
Solar wind as a turbulence laboratory

• Characteristics
  – Collisionless plasma
  – Variety of parameters in different locations
  – Contains turbulence, waves, energetic particles

• Measurements
  – In situ spacecraft data
  – Magnetic and electric fields
  – Bulk plasma: density, velocity, temperature, …
  – Full distribution functions
  – Energetic particles

• The only collisionless plasma we can sample directly
Interpreting spacecraft measurements

- In the solar wind (usually),
  \[ V_A \sim 50 \text{ km/s}, \quad V_{SW} >\sim 300 \text{ km/s} \]
- Therefore,
  \[ V_{SW} \gg V_A \]
- **Taylor’s hypothesis**: time series can be considered a spatial sample
- We can convert spacecraft frequency \( f \) into a plasma frame wavenumber \( k \):
  \[ k = \frac{2\pi f}{V_{SW}} \]
- Almost always valid in the solar wind
- Makes analysis much easier
- Not valid in, e.g. magnetosheath, upper corona
Interpreting spacecraft measurements

- Solar wind flows radially away from Sun, over spacecraft
- Time series is a one dimensional spatial sample through the plasma
- Measure variations along one flow line
The turbulent solar wind

- Fluctuations on all measured scales

Power spectrum
- Broadband
- Low frequencies: $f^{-1}$
- High frequencies: $f^{-5/3}$
Active turbulent cascade in fast wind

- Fast wind: “knee” in spectrum
- Spectrum steepens further from the Sun
- Evidence of energy transfer between scales: turbulent cascade

after Bavassano et al 1982
**Interpretation**

- Initial broadband 1/f spectrum close to Sun
- High frequencies decay, transfer energy
- Spectrum steepens
- Progressively lower frequencies decay with time (distance)
- Breakpoint in spectrum moves to lower frequencies

- **Breakpoint is the highest frequency unevolved Alfvén wave**
Alfvén waves

Field-parallel Alfvén wave:
- B and V variations anti-correlated

Field-anti-parallel Alfvén wave:
- B and V variations correlated
- See this very clearly in the solar wind
- Most common in high speed wind
Propagation direction of Alfvén waves

- Waves are usually propagating away from the Sun.

Average magnetic field anti-sunward
Negative correlation
Propagating parallel to field
Propagating away from Sun in plasma frame
Dominance of outward-propagating waves

- Solar wind **accelerates** as it leaves the corona
- Alfvén speed **decreases** as field magnitude drops
- Alfvén critical point: equal speed (~10-20 solar radii)
- Above critical point, all waves carried outward

Therefore,

- Outward-propagating low frequency waves **generated in corona**!
Waves and motion in the chromosphere
Currently interesting questions

• Anisotropy: what is the effect of the magnetic field?

• Kinetic scales: how is energy transferred and dissipated below the ion gyroscale?

• Turbulent structures: does plasma turbulence generate discrete structures?
Importance of the magnetic field

- Magnetic field is often used for turbulence analysis
- Precise measurement
- High time resolution
- Low noise
- For MHD scales, this is often sufficient
- (but more about velocity later...)
- For kinetic scales, have to be more careful
Field-aligned anisotropy

- Power levels tend to be perpendicular to local magnetic field direction
- \(\rightarrow\) anisotropy

- Dots: local minimum variance direction
- Track large scale changes in field direction

- Small scale turbulence “rides” on the back of large scale waves
Anisotropic MHD turbulence

Anisotropy of energy transfer

Neutral fluid
• No preferred direction
  → isotropy

Plasmas
• Magnetic field breaks symmetry
  → anisotropy

• Shebalin (1983): power tends to move perpendicular to magnetic field in wavevector space

• Goldreich and Sridhar (1995): “critical balance” region close to $k_{\parallel}=0$
Critical balance

- Goldreich and Sridhar, 1995
- Balance of Alfvén and nonlinear timescales
- Distinguish hydro-like and MHD-like regimes
- What is nature of cascade around this regime?
Anisotropic energy transfer

Wavevectors
- Energy tends to move perpendicular to magnetic field

Eddies
- On average, tend to become smaller perpendicular to field
- Results in long, fine structures along the magnetic field

Hydrodynamics
MHD

Anisotropic MHD turbulence
Anisotropy and 3D field structure

- Wavevectors parallel to the field: long correlation lengths perpendicular to field (“slab”)
- Wavevectors perpendicular to the field: short correlation lengths perpendicular to field (“2D”)

- Mixture of slab and 2D results in shredded flux tubes
- Consequences for field structure and energetic particle propagation

Matthaeus et al 1995
Evidence for critical balance?

- Wicks et al., 2011
- Track local magnetic field, using wavelets
- Perp spectrum: 5/3
- Parallel spectrum: 2
- This is what is predicted for reduced spectrum from critical balance
- Is this a proof of CB?
Kinetic processes

- What happens when we reach non-MHD scales?
- Kinetic processes important
- Hydrodynamics: viscosity causes dissipation
- Collisionless plasmas: no real viscosity
- What causes dissipation?
- Waves become dispersive
Spectrum at Small Scales

- What happens when cascade reaches special plasma scales, e.g., gyroradius?
- Scale invariance broken so change in power law spectrum, it steepens
- What physical processes cause this?
  - new type of cascade
  - energy dissipation
- Nature of the fluctuations
  - kinetic Alfven
  - dispersive modes
  - more compressible
  - natural extension of large scale cascade

Alexandrova et al. 2009 PRL
Chen et al. 2013 PRL
Discontinuities vs turbulence

• Turbulence
  – Field-perpendicular cascade generates short scales across the field
  – Tube-like structures
  – Not topological boundaries

• Flux tubes
  – Sourced from Sun (Borovsky)
  – Topological boundary?

• How to decide?
  – Composition changes?
Intermittency & Structures

• Plasma turbulence also intermittent, but tends to generate 2D sheets

• Solar wind structures: current sheets, discontinuities, reconnection events, etc.

• Turbulence generated vs plasma boundaries

Boldyrev & Perez 2012 ApJL
Dissipation and Heating

- How is the turbulent energy finally dissipated?
- How can “collisionless” plasmas be heated?
- Several mechanisms proposed
  - cyclotron damping
  - stochastic heating
  - Landau damping (+ entropy cascade)
  - reconnecting current sheets
- What constitutes irreversible heating? Are collisions required or are wave-particle interactions enough?
- These are currently some of the big questions in space plasma physics
**Kinetic instabilities**

- Evidence for evolution of kinetic distribution limited by instabilities
- Instability thresholds for ion cyclotron (solid), the mirror (dotted), the parallel (dashed), and the oblique (dash-dotted) fire hose
- Figure from Matteini et al., 2007
Evidence for instability-generated fluctuations

- Bale et al., PRL, 2009

- Intervals near instability thresholds seem to generate fluctuations locally.

- Process which keeps distributions near instabilities.

- What fraction of observed power is due to instabilities?
Some unanswered questions

3D structure
• What is the 3D form of the turbulence, particularly the magnetic field?
• How does this control energetic particle transport?

Dissipation
• Mechanism?
• Role of instabilities?

Coronal heating
• What can we learn about coronal conditions from the solar wind?
Summary

Anisotropy
• Perpendicular cascade
• K41-type cascade

Intermittency
• Similar to hydro

Kinetics
• Ultimate dissipation processes unclear