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
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
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

D. Vier/SoHO/Hubble/Dimotakis et al
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
The turbulent solar wind

- Fluctuations on all measured scales

Power spectrum
- Broadband
- Low frequencies: $f^{-1}$
- High frequencies: $f^{-5/3}$
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
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
Interpreting spacecraft measurements

• In the solar wind (usually),
  \[ V_A \sim 50 \text{ km/s}, \ V_{SW} > 300 \text{ km/s} \]
• Therefore,
  \[ V_{SW} >> V_A \]
• **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
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
Summary: spectral index in fast wind

- Ulysses polar measurements
- Magnetic field component
- Inertial range
- Development of cascade
- $1/f$ Alfvén waves at low frequencies

Not shown or considered here:
- Dissipation at higher frequencies
- Structures at lower frequencies

![Graph showing spectral index vs. log frequency with regions labeled Alfvén waves, Inertial range, Dissipation, and Structures.](image)
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 \textit{away} from the Sun

\textbf{Average magnetic field anti-sunward}
Negative correlation
Propagating parallel to field
Propagating \textit{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?
Field-aligned anisotropy

- Power levels tend to be perpendicular to local magnetic field direction
  \[ \rightarrow \text{anisotropy} \]

- 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
Anisotropy and 3D magnetic field structure

**Slab**
- Plane waves
- Infinite correlation length perpendicular to magnetic field
- Flux tubes stay together

**2D (+slab)**
- Finite perpendicular correlation length
- Flux tubes “shred”
  → Field-perpendicular transport
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
The reduced spectrum

- For a given spacecraft frequency $f$, this corresponds to a flow-parallel scale
  $\lambda = \frac{V_{SW}}{f}$
- …and a flow-parallel wavenumber
  $k_\parallel = \frac{2 \pi f}{V_{SW}}$
- But sensitive to all waves with
  $k \cdot V_{SW} = 2 \pi f$

→ “reduced spectrum”
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
Steeper spectrum at kinetic scales

Fig. 1. (a) Energy spectra of $B$ fluctuations measured by Cluster (full line) and by Helios 2 (dashed-dotted line) with power law fits; vertical lines indicate the ion cyclotron $f_{ci} = 0.1$ Hz and spectral break $f_b = 0.8$ Hz frequencies. (b) The flatness for the same data sets and frequencies.

- Alexandrova et al., 2007
- Note: Taylor’s hypothesis not necessarily satisfied
E and B spectrum in the kinetic regime

- MHD: $E = -V \times B$
- Not so on kinetic scales
- Evidence for kinetic Alfvén waves?
- Bale, 2005
- See also: Galtier, Hall MHD
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?
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?
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

Large scale dependence
• Distance/latitude/wind speed variability