Turbulence Observations in Heliospheric Space Plasmas

2. Overview on solar wind

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Why study Solar Wind turbulence?

Has effect on the Earth: Space Weather
• Triggers reconnection, substorms, aurorae, ...

Helps understanding solar processes
• Signature of coronal heating, ...

Relevant for energetic particle transport and acceleration
• Controls cosmic rays throughout the solar system

Helps understanding astrophysical plasmas
• Stellar formation, jets, intergalactic medium, ...

Relevant for laboratory plasmas
• Reduces confinement in fusion devices

Turbulence as a universal phenomenon
Comparison with hydrodynamics and complex flows

Fundamental plasma processes
• Dissipation of energy, magnetic reconnection, propagation of waves, ...

The solar wind as a wind tunnel
Early results: solar wind heating

Measured solar wind temperature decreases radially less than expected from adiabatic expansion: something is heating the plasma. A candidate: dissipation of energy at the bottom of a turbulent cascade. Just one of many observations motivating the study of turbulence.

\[ T \sim T_0 (r_0/r)^\xi \]

\[ \xi \theta \left[ 0.7 \quad 1 \right] \]

(Matthews et al, 1999)
Autocorrelation function

Examples of Autocorrelation function in the solar wind

J. T. Gosling  S. J. Bame

JOURNAL OF GEOPHYSICAL RESEARCH VOL. 77, NO. 1 12 JANUARY 1, 1972

Correlation scale: ~ a few days

Fig. 11. Autocorrelation of Vela 2 and 3 data near zero lag using 3-hour averages of the data July 1964 to December 1967. Significant correlations extend out to a lag of about 75 hours.

Vela 2 and Vela 3 data, 1964-1967

Fig. 2. Autocorrelation of the solar-wind flow speed for the interval July 1964 to December 1967 using daily averages (upper curve) and 3-hour averages (lower curve).

Recurrence scale: 28 day (solar rotation)
Combined dataset from ACE and Wind at different distances (lags)

**TABLE I.** Summary of data intervals used for this analysis.

<table>
<thead>
<tr>
<th>Data set</th>
<th>Separation ($R_E$)</th>
<th>Length</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACE-Wind</td>
<td>20–350</td>
<td>2 d</td>
<td>264</td>
</tr>
<tr>
<td>Cluster (I)</td>
<td>0.44–1.21</td>
<td>2–16 h</td>
<td>30</td>
</tr>
<tr>
<td>Cluster (II)</td>
<td>0.024–0.042</td>
<td>1–35 h</td>
<td>102</td>
</tr>
</tbody>
</table>

\[ R_{\text{eff}}^m = \left( \frac{\lambda_c}{\lambda_T} \right)^2 \approx 230000. \]

**FIG. 1.** Estimates of correlation function $R(r)$ from 264 ACE-Wind samples, for separation distances 20–350 $R_E$. A fit to a constrained $[R_{\text{DD}}(0) = 1]$ exponential (dashed line) gives correlation scale $\lambda_c = 186R_E$. 

Spatial Correlation of Solar-Wind Turbulence from Two-Point Measurements


Autocorrelation function/2

Examples of Autocorrelation function in the solar wind
Examples of Autocorrelation function in the solar wind (WIND data) and in the magnetosheath (MMS data)

**Solar wind @1AU**
Estimated correlation timescale ~1h
Strongly variable: ranges from ~30min to ~12h in the literature

**Magnetosheath with KHI**
Estimated correlation timescale ~20sec
Estimated KH roll-up: ~70sec

Panebianco, in preparation
Spectra

Magnetic spectra: turbulent solar wind ($f^{-5/3}$). Evidence of radial evolution in Fast wind. 1/f range: uncorrelated (Alfvénic?) fluctuations?

Bruno & Carbone 2013

Variety of spectral indexes are observed: sensitivity to “junk” fluctuations? Physics of the cascade?

WIND, 2004-2009; Chen et al., 2013
Spectra/3

....and they depend on SW parameters

Figure 5. Dependence of spectral indices on (a) solar wind speed $v_{sw}$, (b) magnitude of imbalance $|\sigma_c|$, (c) collisional age $A_c$, and (d) fluctuation amplitude $\delta B / B$. The error bars represent 2 standard errors of the mean. The black dotted lines correspond to different spectral index predictions.

(A color version of this figure is available in the online journal.)
Spectra/4: anisotropy

Unlike neutral flows, MHD turbulence is anisotropic. Components transverse to the mean magnetic field have more power, and spectral exponents depend on the $k-B_0$ angle. Also predicted by MHD simulations: convection of Alfvénic fluctuations decorrelates and inhibits the nonlinear interactions in the $\parallel$ direction. Not sufficient to explain observed anisotropy (see e.g. Oughton, 1994)

Variance anisotropy: $\delta B_\perp \neq \delta B_\parallel$

Power anisotropy: $P(k_{\perp}) \neq P(k_{\parallel})$

Wavevector anisotropy: $k_{\perp} \neq k_{\parallel}$

Spectral index anisotropy: $\alpha_{\perp} \neq \alpha_{\parallel}$

Imbalance: $E^+ \neq E^-$

[Horbury, Wicks & Chen 2012 SpaceSciRev]
Spectra/5: anisotropy

Critical balance [Goldreich & Sridhar, 1995]:

\[ \tau_A \approx \tau_{NL} \rightarrow k_\parallel \sim k_{\perp}^{2/3} \text{ (eddies get elongated)} \rightarrow E(k_{\perp}) \sim k_{\perp}^{-5/3}, E(k_{\parallel}) \sim k_{\parallel}^{-2} \]

Observed spectral exponents seem to confirm the prediction.

Caveat: use of wavelet-based locally defined, scale-dependent mean magnetic field. Is this OK?
Open questions: How to define (local or global) $B_0$ in a turbulent flow with fluctuations at all scales? Meaningful in terms of theoretical models? ~Lagrangian turbulence? OK in time series? Mixing longitudinal and transverse fluctuations?
Early observations of high frequency spectra showed a secondary power-law range, with very variable spectral index [2-4] (claim of dissipation range).

Leamon et al., 1998
There is now a certain amount of agreement about the spectral properties after the ion-scale break [\(\sim 2.5-2.8, \frac{7}{3}, \frac{8}{3} \ldots\)]. Something more complicated happens in the transition zone. 

Caveat: very short samples, ergodicity might be violated.
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Caveat: very short samples, ergodicity might be violated.
**Spectra/9: spectral break**

(or \( f_b \) vs \( f_{ci} \) vs \( f_{\lambda i} \) (Hall) vs \( f_{pi} \) (kinetic Alfvén turbulence) vs \( f_r \) (Alfvén waves resonance)…)

Disagreement on the location of the spectral break \( f_b \) (important to understand which processes end the MHD cascade).

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**Ion inertial length**

(Leamon, 2000)

**The first scale to break MHD?**

(Chen et al., 2014)

**Resonance condition for ||-propagating Alfvén waves?**

(Bruno & Trenchi, 2014)
Radial distance evolution of the spectral break: even more controversial data.

Decreasing (Messenger/Wind/Ulysses alignment)?
Bruno & Trenchi 2014

Increasing?
Bourouaine et al., 2012

Constant Helios2+Ulysses)?
Perri et al., 2010
And of course spectra are anisotropic at kinetic scales

Chen et al. 2010 PRL
Kiyani et al., 2013

Consistently with several models, magnetic fluctuations become more compressible at small scales. Typical relative power in $\delta B_\parallel$ increases from 5% to 30% [Salem et al., 2012].

Turner et al., 2011

Spectra/(n-1): compressive
Density fluctuations are enhanced (shallower spectra) in the transition range, where compressive magnetic fluctuations also start to enhance.
Spectra/(n+1): electric field

Electric field measurements show a spectral flattening above the ion-scale break, where it decouples from the magnetic field. Parallel electric field also show more power than expected. In the inertial range, it couples to B in the s/c frame, and to velocity in the plasma frame. At small sales: faster decay.
Spectra/$\infty$: electron scale

A second break occurs at electron scales. The spectral shape after the break is debated, but limited data resolution and steep decrease don’t allow an answer.
SW turbulence is highly intermittent: energy is transferred on concentrated small scale structures.

- Generation of small scale structures
- Depends on SW speed, radial distance, solar activity, and more generally on SW conditions.
- Good agreement with multifractal models for intermittent turbulence

Burlaga 1991; Marsch & Tu 1994; Carbone 1996; Horbury 1998; Sorriso-Valvo 1999, 2000; ...
Intermittency/2: radial evolution

Radial increase of intermittency may be the result of developing turbulence, or decrease of uncorrelated (Alfvénic) fluctuations (in fast wind).

Pagel & Balogh, 2003

PDF fitting parameter, related with the kurtosis

$\lambda^2$ and $\sigma_0^2$ at $\tau = T$
Intermittency at high frequency is more variable: some SW samples show increase of Flatness (typically with a small flattening/decrease around the spectral break, suggesting phase re-organization), or linear scaling of the structure functions (no intermittency). It is probably a very local property.

Gives information about the nonlinear character of the high frequency energy cascade, and on formation of smaller scale structures.
Intermittency/4: small scale

Wu et al., 2013

MMS magnetic field data in the magnetosheath (during KHI)

Panebianco, in prep.
Intermittency highlights the enhanced presence of small scale magnetic structures in solar wind turbulence. These structures have been described and studied in several works [Tsurutani & Smith, 1979; Tu & Marsch, 1995].

Detection techniques are based on wavelet power threshold (e.g. the Local Intermittency Measure) [Veltri & Mangeney 1999; Bruno 2001] or variance threshold (PVI) [Greco 2008; Greco & Perri, 2014].

\[
PVI_{\Delta t, t} = \frac{|\Delta B(t, \Delta t)|^2}{\langle |\Delta B(t, \Delta t)|^2 \rangle},
\]

\[
LIM_{\Delta t, t} = \frac{|\tilde{b}_{\Delta t, t}|^2}{\langle |\tilde{b}_{\Delta t, t}|^2 \rangle},
\]
Heating and acceleration near intermittent structures

Enhanced heating near PVI structures
[Osman et al., 2012]

\[(T_p r_\delta + \Delta T_\delta) \times 10^5 \text{ K}\]

\[\Delta r \times 10^5 \text{ km}\]

Enhanced SEP near PVI structures
[Tessein et al., 2013]

Aver. EPAM Flux (particles/cm\(^2\)S\(^\text{sec}\))

Chiasapis et al., 2015

\[\Delta T_e \text{ (eV)}\]

PVI index

Servidio et al., 2012

\[\text{flux}\]

\[\text{mag}\]
Third-order moment scaling law

**Fluids** - Yaglom law: linear scaling of the 3\textsuperscript{rd} order moment: \( \Delta v_i^3 = -\frac{4}{5} \epsilon l \)

**MHD** - Politano-Pouquet law: linear scaling of the *mixed* 3\textsuperscript{rd} order moment.

\[
Y^\pm(\ell) = \langle |\Delta z^\pm(\ell;x)|^2 \Delta z^\mp_R(\ell;x) \rangle = -\frac{4}{3} \epsilon^\pm \ell
\]

\[
Z^\pm(x,t) = v^\pm \frac{B}{\sqrt{4\pi\rho}}
\]

1997, days 1-9 (fast)

**Ulysses - Solar wind**
McBride et al., 2005, 2008
Sorriso-Valvo et al., 2007, 2010
Marino et al., 2008, 2011
Mean and local energy transfer rate

Politano-Pouquet: first measurement of the mean energy transfer rate: $2\varepsilon = \varepsilon^+ + \varepsilon^-$

$$Y^\pm (\ell) = \langle |\Delta z^\pm (\ell; \mathbf{x})|^2 \Delta z_{R \ell} (\ell; \mathbf{x}) \rangle = -\frac{4}{3} \varepsilon^\pm \ell$$

$\varepsilon^\pm (t) = \frac{|\Delta z^\pm (t) |^2 \Delta z_{R \ell} (t)}{\tau \langle v \rangle}$

*A proxy for the local energy transfer rate*

Includes velocity, magnetic field and coupled terms

Marsch & Tu, 1997
Sorriso-Valvo et al., 2015
Comparison with PVI: Helios, Wind

- **Helios II, slow wind**
  - $R=0.35$ AU, $\tau=81$ sec, $C_{r,PVI}=0.89$
  - $\sqrt{\epsilon}$ vs. time

- **Helios II, fast wind**
  - $R=0.54$ AU, $\tau=81$ sec, $C_{r,PVI}=0.82$
  - $\sqrt{\epsilon}$ vs. time

- **Wind, fast wind (2008)**
  - $R=1$ AU, $\tau=3$ sec, $C_{r,PVI}=0.65$
  - $\sqrt{\epsilon}$ vs. time
Statistical properties of proxies: PDF

PDF changes with the scale (intermittency) [Frisch, 1995]

E: stretched exponential fit extreme deviations theory [Frisch & Sornette 1997]

PVI: lognormal fit multiplicative cascade [Kolmogorov 1962]
Statistical properties of proxies: scaling

1/f range

Fluid inertial range

Stretched exponential fitting parameter

Weaker intermittency

Stronger intermittency

Lognormal fitting parameter

Helios II, fast wind, R=0.98AU

Extreme deviations theory:
scaling exponent
\( \sim 1/n \)

n: number of fragmentations in the cascade.

Inertial range:
\( n \sim 12 \)

1/f range:
\( n \sim 3 \)
Proton heating near ε and PVI structures

Osman et al., 2012

Helios II, fast wind, R=0.98AU

Wind, fast wind, R=1AU

Osman et al., 2012
• There are many proposed mechanisms for dissipation of plasma turbulence.
  – What is the relative contribution to dissipation by each of these mechanisms?
  – How is dissipated turbulent energy divided between alphas, protons and electrons?
  – Do we need to challenge some assumptions, e.g. universality?

• What is the most appropriate theoretical framework in which to interpret dissipation range fluctuations?
  – We need to investigate the degree of nonlinearity scale-by-scale and compare to inertial range.
  – What are the most relevant wave modes and how do we distinguish between them?
Summary/2

- What are the roles of current sheets, coherent structures and intermittency in dissipation?
  - How are these structures related to magnetic reconnection?
  - What are the origins of these structures?
  - Need a more robust estimate of the relative importance of current sheets and wave modes?

- This field of work is directly relevant to new missions: NASA MMS, DSCOVR, Solar Probe+ and ESA Solar Orbiter.
  - These will help address the role of turbulent reconnection and the radial evolution of turbulence.
  - What does the plasma turbulence community need that these missions do not provide?