Evolution of plasma turbulence in the solar wind and near Earth’s space

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- Motivation
- Region of interest
- Spacecraft observations of turbulence in:
  - solar wind
  - magnetosheath
  - foreshock
  - high-altitude cusp
A 3D picture of the continuous turbulence development through multiscale regions from direct measurements

- solar wind
- bow shock
- magnetosheath
- magnetopause
- cusp

Ulysses
Cluster
Polar

2-D Global Hybrid Simulations (D. Krauss-Varban, SSL, Berkeley)
Near Earth’ space

**Solar wind** – supersonic and superalfvén outflow of $e^-$ and $p^+$

**Foreshock** – reflected by the bow shock electrons and ions; ULF waves; wave-particle interactions

**Magnetosheath** – heated and slowed down solar wind plasma; magnetic field and plasma fluctuations intensified downstream quasi-parallel shock
The Earth's magnetosphere

Magnetopause – boundary separating solar wind and magnetospheric plasma

The Earth's cusp

Cusp – depressed and irregular magnetic field; magnetosheath plasma; plasma of ionospheric origin

Near Earth space – complex, highly fluctuating, non-stationary, assumptions fail.
Solar wind fluctuations and magnetic field are highly non-uniform

- depend on location and time and heliospheric conditions
- dynamical interaction different solar wind fast and slow streams
- differences in the fast or slow streams
- differences within the same stream (fast or slow)

Solar wind type is best determined from the distribution of charge states of oxygen ions ($O^{+7}/O^{+6}$ - coronal temperature) rather than from kinetic parameters

Ulysses data (equatorial plane, polar regions from Sun to Jupiter)
SOLAR WIND TYPES

‘pure’ slow – long periods of low speed

slow streams – low speed separated from the mixed

‘pure’ fast – polar fast wind

fast streams – high speed separated from the mixed

[Yordanova et al., 2009, JGR]
Power spectra  \[ P(f) \]

Structure functions  \[ S^n(r) = \left\langle \left| \vec{b}_i(x + \vec{r}) - \vec{b}_i(x) \right|^n \right\rangle \]

(differences of the field separated by a distance \( r \) represents characteristic fluctuations at the scale \( r \))

Flatness  \[ F(r) = \frac{\left\langle S^4(r) \right\rangle}{\left\langle S^2(r) \right\rangle^2} \]

(the signal is intermittent if the flatness increases toward the smaller and smaller scales)

Taylor hypothesis  \[ f = 1 / \Delta t \quad k = 2\pi f / V_{SW} \]
Decreasing the window (scale) the intense fluctuations become more visible and important.
**21 data samples**

- **Range (AU)**: 1.5 – 5.4 AU
- **Heliolatitude**: 25°S - 80°N
- **Pure slow**
- **Slow stream**
- **Pure fast**
- **Fast stream**

*Ulysses Observations NWW, San Diego, March 2013*
“Pure” slow wind

Fast stream

\[ S_q \sim f^{-(1.61 \pm 0.01)} \]

\[ \xi_q \sim f^{-(1.47 \pm 0.02)} \]
\[ F = 3 \text{ (Gaussian)} \]

\[ \Delta t = 0.01 \text{ h } \text{fast} \ (780 \text{ km/s}) \]

\[ \Delta t = 0.02 \text{ h } \text{slow} \ (430 \text{ km/s}) \]
### SOLAR WIND: RESULTS

**PSD**

|                | \(b_R\) | \(b_T\) | \(b_N\) | \(|B|\)     |
|----------------|---------|---------|---------|------------|
| Pure fast      | 1.63    | 1.65    | 1.66    | 1.31       |
|                |         |         |         | \((1/f\text{-like})\) |
| Fast streams   | 1.64    | 1.68    | 1.71    | 1.48       |
|                |         |         |         | \((Kraichnan\text{-like})\) |
| Pure slow      | 1.66    | 1.68    | 1.66    | 1.68       |
|                |         |         |         | \((Kolmogorov\text{-like})\) |
| Slow streams   | 1.76    | 1.82    | 1.69    | 1.73       |
|                |         |         |         | \((\sim 1.8)\) |

**Flatness**

<table>
<thead>
<tr>
<th></th>
<th>(b_R)</th>
<th>(b_T)</th>
<th>(b_N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pure fast</td>
<td>8.2</td>
<td>8.3</td>
<td>8.9</td>
</tr>
<tr>
<td>Fast streams</td>
<td>16.1</td>
<td>16.2</td>
<td>15.2</td>
</tr>
<tr>
<td>Pure slow</td>
<td>25.5</td>
<td>35.5</td>
<td>23.1</td>
</tr>
<tr>
<td>Slow streams</td>
<td>17.3</td>
<td>25.2</td>
<td>19.2</td>
</tr>
</tbody>
</table>

**Lat AU**

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>Pure fast</td>
<td>10°S – 10°N,</td>
<td>5.4</td>
</tr>
<tr>
<td>Fast streams</td>
<td>25°S – 30°N,</td>
<td>1.5 - 5</td>
</tr>
<tr>
<td>Pure slow</td>
<td>50°S – 80°N,</td>
<td>1.5 - 3</td>
</tr>
<tr>
<td>Slow streams</td>
<td>10°S – 30°N,</td>
<td>1.5 - 4.5</td>
</tr>
</tbody>
</table>

\(\Delta t = 0.01\ h\ \text{fast (780 km/s)}\)

\(\Delta t = 0.02\ \text{slow (430 km/s)}\)
Conclusions

- **Turbulence nature** – for different solar wind types is different, because of the different region of origin in the solar corona.
  - *fast wind* – slowly developing turbulence
  - *slow wind* - developed turbulence

- **Intermittency** – regardless of the type of the solar wind, the turbulence is intermittent.
  - *least* intermittent is the pure *fast wind*
  - *most* intermittent is the pure *slow wind*
  - *fast streams* less intermittent than *slow streams*

- **Radial evolution** – pure *fast* wind evolves towards MHD-like turbulence and it is the only type showing evolution; higher estimation of flatness.

- **Solar activity** – during and close to solar *minimum* we can observe different solar wind types; around solar *maximum* expect turbulence properties similar to the pure *slow wind*. 
Turbulence behind a quasi-parallel shock

[Omidi et al., 2005, JGR]

[Yordanova et al., 2008, PRL]
Power spectral density

(0.33 – 2.5 Hz)
0.3 – 4 s
150 - 1100 km
2 - 15 c/ωpi
(V_{msh} ~ 375 km/s)
Wavelet based partition function (Muzy et al., 1991):

\[ Z(q,a) \sim a^{\tau(q)}, \quad Z(q,a) = \sum_{l \in L(a)} \left( \sup_{a' \leq a} |T_{\psi}(g)(b_l(a'), a')| \right)^q \]

Models

1. P-model (Meneveau & Sreenivasan, ’87,’91):

\[ \tau(q) = -\log_2 \left[ P^{\xi_q} - (1 - P)^{\xi_q} \right] \]

   - \( P_1 = 0.5 \) - no intermittency
   - \( P_1 = 1 \) - fully intermittent case

2. Extended SF (Tu et al., ’96, Marsh & Tu, ’97):

   - (Kolmogorov-like cascade)

\[ \tau(q) = \left( -\frac{5}{2} + \frac{3}{2} \alpha \right) \frac{q}{3} - \log_2 \left[ P^{\alpha q/3} + (1 - P)^{\alpha q/3} \right] \]

   - (Kraichnan-like cascade)

\[ \tau(q) = (-3 + 2\alpha) \frac{q}{4} - \log_2 \left[ P^{\alpha q/4} + (1 - P)^{\alpha q/4} \right] \]
Conclusions

- The magnetosheath turbulence at spatial scales 2-15 c/ω_{pi} is **not in a fully developed state** after the shock crossing.

- There is a clear **anisotropy** of the turbulence with respect to the shock normal.

- There is **small intermittency** and **no anisotropy** in the frequency range between 3-10 Hz (25-125 km).
Magnetic field turbulence in the solar wind, foreshock and magnetosheath

ANISOTROPY IN THREE REGIONS

[Sorriso-Valvo et al., 2010, EPL]
The \( n \)-th order 3D structure function tensor:

\[
S_{\alpha_1, \alpha_2, \ldots, \alpha_n} (l) = \left[ B_{\alpha_1} (r + l) - B_{\alpha_1} (r) \right] \times \\
y \left[ B_{\alpha_2} (r + l) - B_{\alpha_2} (r) \right] \times \ldots \\
y \left[ B_{\alpha_n} (r + l) - B_{\alpha_n} (r) \right] \right]
\]

\( \alpha_1 = \alpha_2 = \ldots = \alpha_n = r \) – ordinary \( n \)-th structure function

The 2\textsuperscript{nd} order structure function tensor:

\[
S_{\alpha\beta}, \ (\alpha, \beta = x, y, z)
\]

\( \alpha \neq \beta \) – purely anisotropic part

\( \alpha = \beta \) – both anisotropic and isotropic parts
Scaling properties of anisotropy in the solar wind, foreshock and magnetosheath turbulence

Sxx, yy, zz - isotropic and anisotropic contributions
Sxy, yz, xz - describe the degree of correlations present between the different components of the field fluctuations; non-vanishing terms -> anisotropy

Decorellation - SW - 2 min
             - FS – 5 sec
             - MSH – 20 sec

[Sorriso-Valvo et al., EPL, 2010]
ANISOTROPY IN THREE REGIONS

Structure function fit

Batchelor’s relation:

\[ S_{\alpha_1,\ldots,\alpha_n}(l) = \frac{A_{\alpha_1,\ldots,\alpha_n} \eta^n (l/\eta)^n}{\left[1 + B_{\alpha_1,\ldots,\alpha_n} (l/\eta)^2\right]^{C_{\alpha_1,\ldots,\alpha_n}}} \times \left[1 + D_{\alpha_1,\ldots,\alpha_n} (l/L_0)^2\right]^{2C_{\alpha_1,\ldots,\alpha_n}-n} \]

\[ L_0 = \frac{\int E(k) k^{-1} dk}{\int E(k) dk} \quad \text{Integral scale} \]

\[ \eta \sim \lambda_T = \sqrt{\frac{\int E(k) dk}{\int E(k) k^2 dk}} \quad \text{Dissipation scale} \]

Integral scale:
- SW ≈ 110000
- FS ≈ 70000
- MSH ≈ 40000

Dissipation scale:
- SW = 4000 km
- FS = 5000
- MSH = 2000

Relation between \( \zeta \) and \( C \):

\[ \zeta_{\alpha_1,\ldots,\alpha_n} = n - 2C_{\alpha_1,\ldots,\alpha_n} \]

Results

The difference between the diagonal and off-diagonal scaling exponents is very small – anisotropy presence at small scales; decay rate comparable to the longitudinal and transverse structure function.

<table>
<thead>
<tr>
<th>( \zeta_{\alpha_1,\alpha_2} )</th>
<th>FS</th>
<th>SW</th>
<th>MSH</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \zeta_{xx} )</td>
<td>1.62 ± 0.16</td>
<td>1.15 ± 0.07</td>
<td>1.7 ± 0.1</td>
</tr>
<tr>
<td>( \zeta_{yy} )</td>
<td>1.8 ± 0.2</td>
<td>1.0 ± 0.3</td>
<td>1.75 ± 0.18</td>
</tr>
<tr>
<td>( \zeta_{zz} )</td>
<td>1.95 ± 0.05</td>
<td>1.7 ± 0.3</td>
<td>1.88 ± 0.06</td>
</tr>
<tr>
<td>( \zeta_{xy} )</td>
<td>1.63 ± 0.14</td>
<td>1.37 ± 0.09</td>
<td>1.83 ± 0.06</td>
</tr>
<tr>
<td>( \zeta_{xz} )</td>
<td>1.86 ± 0.1</td>
<td>1.0 ± 0.5</td>
<td>1.6 ± 0.3</td>
</tr>
<tr>
<td>( \zeta_{yz} )</td>
<td>1.42 ± 0.5</td>
<td>1.0 ± 0.5</td>
<td>1.74 ± 0.2</td>
</tr>
</tbody>
</table>
Conclusions

- All regions show anisotropic turbulence

- Foreshock and magnetosheath are less anisotropic than the solar wind:
  - due to through the shuffling of the fields occurring in proximity of the bow shock, that could cancel the importance of anisotropy.
  - the presence of a second source of anisotropy (the velocity shear and the other phenomena in proximity of the bow shock) could also contribute to the observed loss of anisotropy.
Two-point structure function of the magnetic field $B$

**Single** point measurements allow structure function calculation only in the direction of the flow.

**Multipoint** measurements allow to characterize magnetic field anisotropy at different angles relative to the flow direction.

$$\Delta S_{\alpha\beta}^{12} \left( \vec{l} \right) = \left\langle \left| \vec{B}_{\alpha\beta}^2 \left( \vec{R} + \vec{l} \right) - \vec{B}_{\alpha\beta}^1 \left( \vec{l} \right) \right| \right\rangle, \quad \alpha, \beta = x, y, z.$$  

$$R \left( \Delta t \right) = d - V_{SW} \Delta t$$

$d$ - initial spacecraft distance  
$V_{SW}$ - solar wind speed in plasma frame
$l = -V_{SW} \Delta t$

$\frac{\vec{V}_{A} \Delta t}{\vec{d} - \vec{V}_{SW} \Delta t} \ll 1,$

$V_{SW} \gg V_{A}$

[Horbury, 2000]
Results

- non-vanishing anisotropic elements towards the small scales
- same order in both anisotropic and mixed elements

Conclusions

- the *return-to-isotropy* assumption does not hold in MHD turbulence
- the anisotropy is not axisymmetric with respect to the mean magnetic field
Wavelet based partition function (Muzy et al., 1991):

\[ Z(q,a) \sim a^{\tau(q)}, \quad Z(q,a) = \sum_{l \in L(a)} \left( \sup_{a' \leq a} |T_{\psi}[g](b_l(a'),a')| \right)^q \]

**Models**

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*(Kolmogorov-like cascade)*

\[ \tau(q) = (-3 + 2\alpha) \frac{q}{4} - \log_2 \left[ P^{\frac{q}{4}} + (1 - P)^{\frac{q}{4}} \right] \]

*(Kraichnan-like cascade)*
Results

Reconnection at subsolar point, plasma flowing on the open field lines towards magnetotail

Kolmogorov – like ($B_z < 0$)

Northern lobe reconnection; turbulent boundary layer - convergence of magnetosheath flow and reconnection associated flow

p – model ($B_z > 0$)

9 Oct 1996

MLat: 55.46 – 70.58
MLT: 12:17 – 12:50
$X_{GSM}$ 3-4 Re, $Y_{GSM}$ 0.5-0.2 Re, $Z_{GSM}$ 7-5 Re

4 Apr 1997

MLat: 59.87° - 67.95°
MLT: 13:40 - 14:17
$X_{GSM}$ 4.2-3.9 Re, $Y_{GSM}$ 1.5-1.6 Re, $Z_{GSM}$ 5-6 Re
Power spectra in parallel and perpendicular directions

\[ f \sim 5/3 \]

\[ \alpha \sim 1.62 \quad \alpha \sim 2.41 \]

MLat: 61 – 67
MLT: 13:40 – 14:13
d_{mp} \sim 2-4 \text{ Re}

\[ B_0 = 91 \pm 9 \text{ nT} \]
\[ \delta B_{1,2} = 0 \pm 6 \text{ nT} \]

[Yordanova et al., 2005, NPG]
Extended Self-Similarity Analysis

\[ S_q(\tau) \sim \left[ S_p(\tau) \right]^{{\eta}_p(q)} \]

\[ S_q(\tau) \sim \tau \]

\[ {\eta}_p(q) \equiv {\zeta}(q) \]

\[ S_q(\tau) \sim \left[ S_2(\tau) \right]^{{\zeta}_q} \leftrightarrow B_0 \]

\[ S_q(\tau) \sim \left[ S_3(\tau) \right]^{{\zeta}_q} \leftrightarrow \delta B_i \]
PDF in parallel and perpendicular directions

\[
\sigma^2_{\Delta B_0}(\Delta B_0^2, \tau)\]

\[
\Delta B_0^2 = B_0^2(t + \tau) - B_0^2(t)
\]

\[
\Delta \delta B^2 = \delta B^2(t + \tau) - \delta B^2(t),
\]

\[
\delta B^2 = (\delta B_1^2 + \delta B_2^2)
\]

\[
\tau = 6, 12, 24, 48, 96, 192\Delta t
\]
Conclusions

- Magnetic field intensity - turbulence depends on IMF:

  \[ B_z > 0 \quad p - \text{model} \quad (\text{fluid, fully developed}) \]
  \[ B_z < 0 \quad \text{Kolmogorov-like} \quad (\text{fluid, non-fully developed}) \]

- Magnetic field components

  PSD - different scaling in parallel and perpendicular directions

  ESS – parallel fluctuations are characterized by quasi-linear (monofractal) nature; perpendicular - by a strong intermittent (multifractal) character

  PDF – more intermittent character of the fluctuations in perpendicular direction then in parallel
Summary for near Earth’s space plasma turbulence

- Solar wind turbulence and the modified turbulence in the near Earth’s plasma regions are both intermittent and anisotropic, however to a different degree.

- The nature of turbulence depends on:
  - the source of origin (Solar corona, Bow shock, Magnetopause)
  - local drivers (Stream/stream interactions in the SW; reflected ions in the FS; velocity shears in the MSH and the cusp; reconnection in the cusp)

- Turbulence is more developed away from boundaries

- Anisotropy and intermittency increases away from boundaries