Turbulence in the solar wind, spectra from Voyager 2 data

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Voyager 2 Interstellar Mission

- **Voyager 2** is flying now at 15.6 km/s, 104.7 AU from Earth, in the *Heliosheath*, the outermost layer of the heliosphere where the solar wind is slowed by the pressure of interstellar gas
- **Termination Shock** was passed on Sep 5, 2007

source: http://voyager.jpl.nasa.gov

A turbulence hypothesis for the magnetic field in the *Heliosheath*  
"Is the magnetic field in the Heliosheath laminar or a turbulent sea of bubbles?"

source: M. Opher et al.
L.L. Orionis colliding with the Orion Nebula. Image from the Hubble Space Telescope, February 1995 (Credit: NASA, The Hubble Heritage Team (STScI/AURA))
Velocity and magnetic field data from V2, period 1979 (DOY 1–180). RTN heliographic reference frame.
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**Year 1979: V and B data**

V2 data in Alfvénic units (1979)

\[
(V - \mu_v), (B/\sqrt{4\pi\rho} - V_A) \text{ (km/s)}
\]

\[
V_R \quad \text{(blue)} \\
B_R \quad \text{(red)}
\]

\[
V_T \quad \text{(blue)} \\
B_T \quad \text{(red)}
\]

\[
V_N \quad \text{(blue)} \\
B_N \quad \text{(red)}
\]
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Year 1979: V and B moments and PDFs

<table>
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<th></th>
<th>μ</th>
<th>σ²</th>
<th>Sk</th>
<th>Ku</th>
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<tr>
<td>V_R</td>
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<td>1893</td>
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<td>B_N</td>
<td>0.10</td>
<td>0.34</td>
<td>-0.24</td>
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</tbody>
</table>

units: km/s, nT

PDF of V and B standardized components and comparison with a Normal distribution Evidence of anisotropy
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Year 1979: V and B moments and PDFs

PDF of standardized modules and comparison with a $\chi^2$ distribution.

High intermittency?

- Evidence of high $Ku(> 3)$
- The origin of “intermittency”: advected coherent structures (flux tubes, etc), stochastic Alfvénic fluctuations generated at solar corona and “frozen” in the wind?
- Intermittency interests a broad range of scales
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Autocorrelations - V2 data (1979, DOY 1-180)

\[ R_{ii}(\tau) = \langle x(t)x(t+\tau) \rangle \]
Cross-correlations tensor: off-diagonal terms

\[ R_{ij}(\tau) = \langle x(t)y(t+\tau) \rangle \]
Cross-correlations tensor: diagonal terms

Summary:

- Averages are computed on 57970 points for V, and 124080 points for B, spanning the whole 180 days period.
- High cross-correlation $V_R B_R \rightarrow$ not in-phase.
- High cross-correlation $V_R B_T \rightarrow$ not in-phase.
- Low Alfvénic one-point correlation (this is often the case in the slow-wind periods.)
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Data reconstruction techniques

V2 velocity and mag. data are discontinuous and irregularly spaced. In the whole year 1979 there is 45% of missing velocity data, 25.4% in the period here considered (DOY 1–180). About mag. data, the percentage is 23.8%. These values are about 97% in 2012.

To perform an accurate spectral analysis on these kind of data sets, a reconstruction technique may be mandatory. In the following, the effect of two interpolation/recovery methodologies on averaged turbulent spectra will be discussed.

- Linear interpolation
- Maximum likelihood reconstruction and realizations constrained by data\(^1\)

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Data reconstruction techniques

To discuss the effects of averaging, interpolating and applying windowing techniques, two 1D sequences of synthetic turbulence data have been generated from imposed spectral properties:

- \( \text{Synt 1} \rightarrow E_{3D}(n/n_0) = \frac{(n/n_0)^\beta}{(n/n_0)^{\alpha+\beta}} \)
- \( \text{Synt 2} \rightarrow E_{3D}(n/n_0) = \frac{(n/n_0)^\beta}{(n/n_0)^{\alpha+\beta}} \times \left[ 1 - \exp\left(\frac{n-n_{tot}}{\gamma} + \epsilon\right) \right] \)

\( \beta = 2, \alpha = 5/3, n_0 = 11, \gamma = 10^4, \epsilon = 10^{-1} \)

The Synt 1 sequence reproduces the Kolmogorov inertial range of canonical turbulence, while Synt 2 reproduces both the inertial and the dissipative part of the spectrum.

- Synthetic data are scaled on a 180 days time grid (\( \Delta t = 100 \text{ s}, n_{tot} = 155520 \))
- The same gaps of V2 velocity data are projected on these sequences
- Spectral analysis is performed. Parameters: \( L_g, L_s \)
Effect of no/linear interpolation on Synt 1 data

Synthetic turbulence1, effects of averaging with no recovery

Synthetic turbulence1, effects of linear recovery, Hann windowing

Synthetic turbulence1, effects of linear recovery, no windowing

Synthetic turbulence1, effects of averaging with no recovery

Spectral analysis: synthetic turbulence

Spectral analysis: methodology and validation

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Effect of no/linear interpolation on Synt 2 data

- Effect of segmentation: increase in slope of about 5% in the inertial range.
- Effect of linear interpolation: function of $L_g$ (length of “filled” gaps). This interpolation transfers energy to the low frequencies, resulting in an increase (about 6%) in the slope, especially in the high-frequency range ($f > 10^{-3}\text{Hz}$).
Effect of no/linear interpolation on Synt 2 data

- Effect of windowing: the Hann window function allows to eliminate spurious energy due to discontinuities ($\approx 1/f$) at the boundary of each segment. The effect is minimal at low wavenumbers. In the high-frequency range, on the one hand a significant increase (up to 23%) of the slope is found to be a function of $L_g$, on the other hand any change in slope of the real spectrum can be followed.

  Energy correction factor for Hann: $1.63^2$

- Without windowing, the segmentation error doesn’t allow to represent the correct slope, in the general case (see the analysis on Synt 2 data). These cases can be recognized by a flattening in the high-frequency range of the spectrum. Averaging long segments helps.
V2 velocity spectra at 5 AU (pre-Jupiter)

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V2 mag. field spectra at 5 AU (pre-Jupiter)

- $B_R^2$ (nT$^2$/Hz)
- $B_N^2$ (nT$^2$/Hz)
- $B_T^2$ (nT$^2$/Hz)

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V2 spectra at 5 AU (pre-Jupiter)

**Velocity:**
- The observed frequency range constitute the inertial range
- All computed slopes ($10^{-4} < f < 2 \cdot 10^{-3}$ Hz) are flatter than the Kolmogorov one:
  \[ \alpha = -1.53 \pm 0.07 \]
- Computed slopes may be slightly overestimated
- A peak is located at $f = 0.0026$ Hz for T and N components: is it physical or instrumentation-related? (no relation with $f_{ci}, f_{pi}, f^*$)

**Magnetic field:**
- Computed slopes ($10^{-4} < f < 2 \cdot 10^{-3}$) are lower than the reference one:
  \[ \alpha = -1.81 \pm 0.09 \]
- Observed steepening for $f > 3 \cdot 10^{-3}$ Hz should not be linked to interpolation issues: the situation recalls that of Synt 2 case, blue (no recovery) and violet (small gaps filled) give the same result.
- Anisotropy is higher with respect to the velocity field
G.B. Rybicki & W.H. Press prediction

- Minimum variance prediction (interpolation):
  \[ y = s + n \]
  \[ s^* = \sum_{i=1}^{M} d_i y_i + x_0 \]
  \[ \hat{s}^* = S^T [S + N]^{-1} y \]
  \[ \hat{s}^* = \text{min. variance estimate for } s^* \]

  Assuming stationary process:
  \[ S_{ij} = \langle s_i s_j \rangle = f(t_i - t_j) \]
  \[ N_{ii} = \langle n_i^2 \rangle \]

  The min. variance estimation is not, however, a typical realization of the underlying process.

- Minimum variance prediction + Gaussian process

  To obtain a typical realization, a Gaussian process is added to the min. var. estimate:
  \[ s_* = u_* + \hat{s}_* \]

  If realizations constrained to data are desired:
  \[ u = V \text{diag}(\lambda_1^{1/2}, \ldots, \lambda_M^{1/2}) r \]
  \[ \lambda_i = \text{eig}(Q), \quad Q = [S^{-1} + N^{-1}]^{-1}, \quad r = \text{rand}(\mu = 0, \sigma^2 = 1) \]
R&P reconstruction

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Final considerations and future development

- **Kolmogorov (-5/3) or Iroshnikov–Kraichnan (-3/2) cascade?**
  Debated question. Many works suggested K41 as the more consistent for SW turbulence (Goldstein, GRL 1995), but in recent works values close to IK for velocity and K41 for mag. field are observed (Safranova et al. PRL 2013 at 1AU, Podesta et al. ApJ 2007, 1AU)
  We provide spectra at 5 AU, supporting these recent observations.

- **The high frequency range. Break frequency/ies, dissipation or further cascades.** Different mechanisms had been proposed to explain the steepening of collisionless SW spectra in the high freq. range (foreshock waves, Landau damping of KAW, wave dispersion). Up to what regime will we be able to observe, in the Heliosheath region?

- **Heliosheath data are very sparse.** How to get reliable spectra when a data loss of 95% is present? We have started to apply the Compressive Sensing technique to this problem. CS is a very recent paradigm for data acquisition, providing reconstruction for a broad class of sparse signals.