Turbulence in the solar wind, spectra from Voyager 2 data

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Turbulent Mixing and Beyond Workshop
ITCP Trieste, 4–9 August 2014

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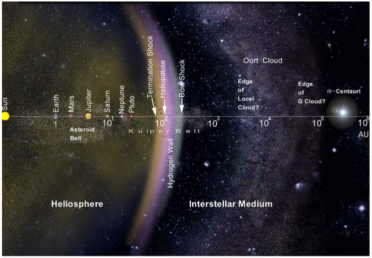
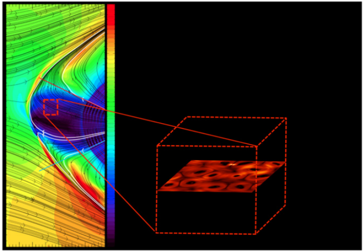
Voyager 2 Interstellar Mission

- *Voyager 2* is flying now at 15.6km/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

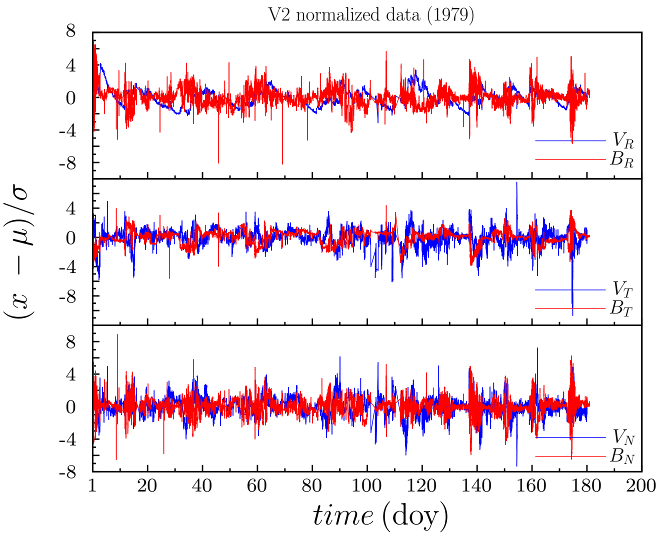


source: M. Opher et al.

A turbulence hypothesis for the magnetic field in the *Heliosheath*
M. Opher et al, ApJ 734, 2011
"*Is the magnetic field in the Heliosheath laminar or a turbulent sea of bubbles?*"

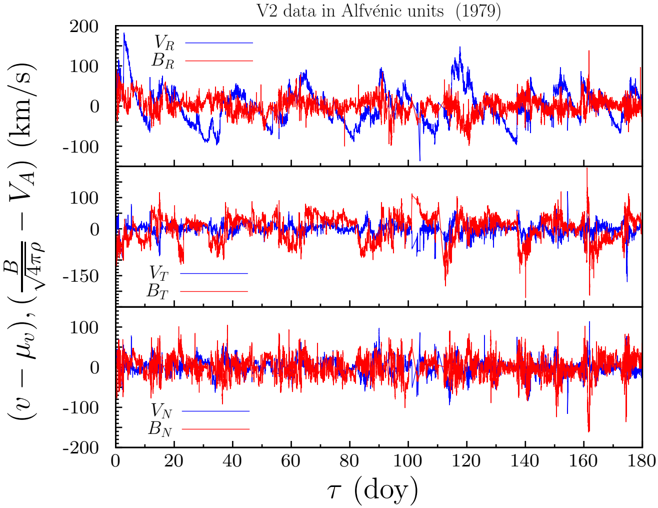
L.L. Orionis colliding with the Orion Nebula.
Image from the Hubble Space Telescope, February 1995
(Credit: NASA, The Hubble Heritage Team (STScI/AURA))

Year 1979: V and B data



Velocity and magnetic field data from V2, period 1979 (DOY 1–180). RTN heliographic reference frame.

Year 1979: V and B data

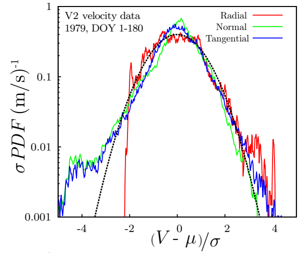


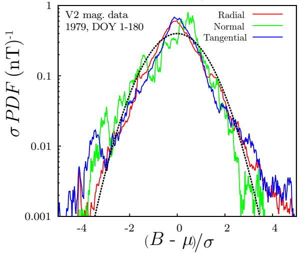
Year 1979: V and B moments and PDFs

	μ	σ^2	Sk	Ku
V_R	454	1893	0.43	3.41
V_T	3.21	252.9	-0.99	7.35
V_N	0.51	250.3	-0.36	5.80
B_R	-0.04	0.173	0.53	6.71
B_T	0.06	0.85	-0.72	10.2
B_N	0.10	0.34	-0.24	7.65

units: km/s, nT

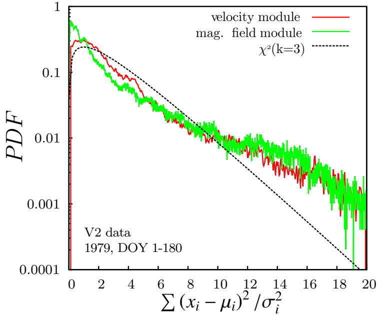
$\langle n_i \rangle$ (cm^{-3})	0.23
$\langle T \rangle$ (K)	27038
β_p	0.225
V_A (km/s)	47.7
c_s (km/s)	19.3
f_{ci} (Hz)	$1.49 \cdot 10^{-2}$
f_{pi} (Hz)	101
$f*$ (Hz)	0.44
r_i (km)	158
λ_D (m)	5.5





PDF of V and B standardized components and comparison with a Normal distribution Evidence of anisotropy

Year 1979: V and B moments and PDFs

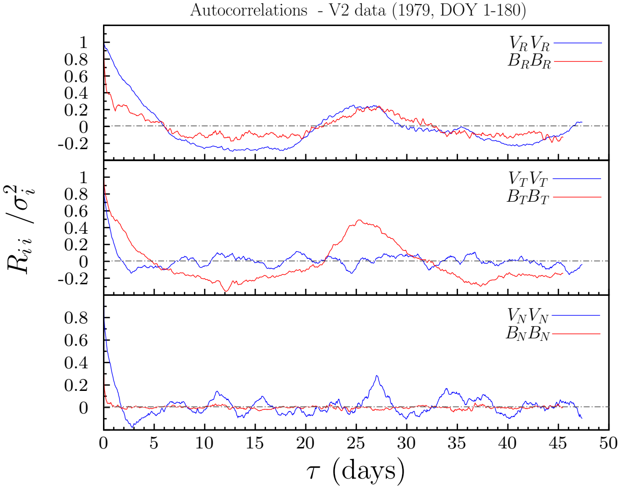


PDF of standardized modules and comparison with a χ^2 distribution.

High intermittency?

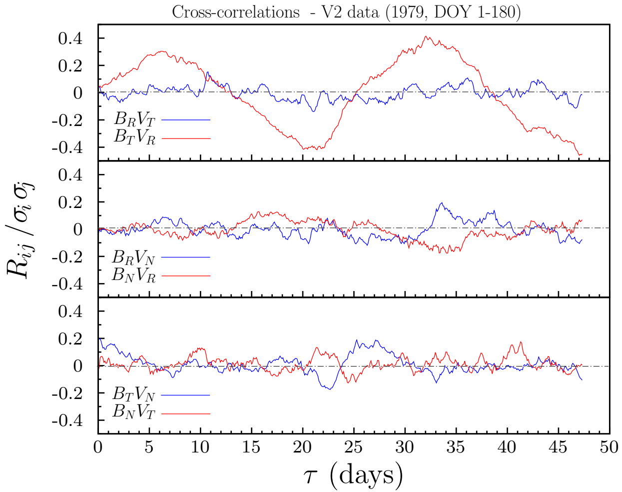
- Evidence of high **Ku**(> 3)
- The origin of "intermittency": advected coherent structures (flux tubes, etc), stochastic Alfvénic fluctuations generated at solar corona and "frozen" in the wind?
- Intermittency interests a broad range of scales

Autocorrelations



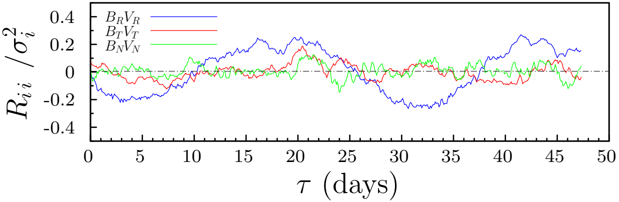
$$R_{ii}(\tau) = < x(t)x(t+\tau) >$$

Cross-correlations tensor: off-diagonal terms



$$R_{ii}(\tau) = < x(t)y(t+\tau) >$$

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
- Evidence of a 25 days periodicity. Minimum of solar activity in 1979
- 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)

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]

[1] Rybicki & Press, ApJ 398, 1992

Data reconstruction techniques

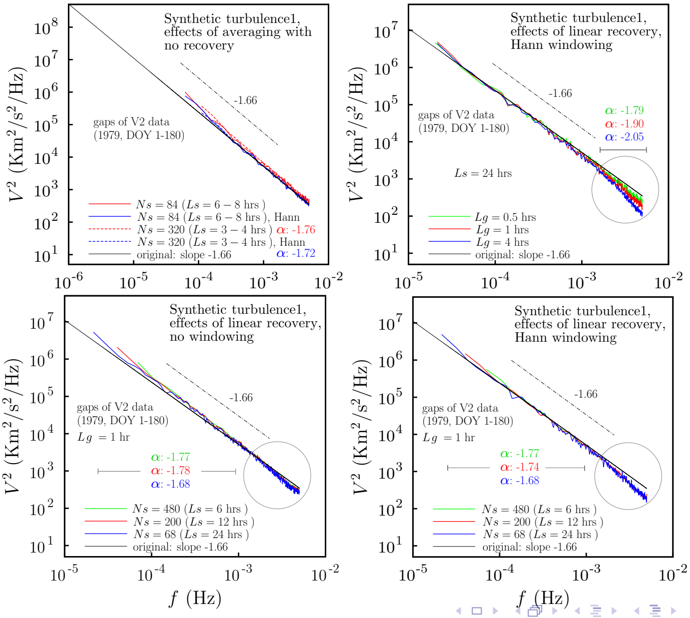
To discuss the effects of averaging,interpolating and applying windowing techniques, two 1D sequences of synthetic turbulence data have been generated from imposed spectral properties:

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

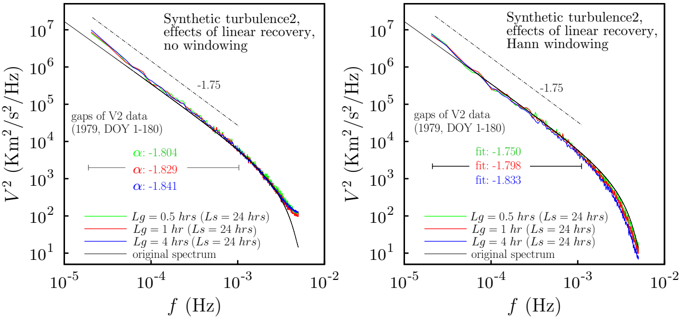
$\beta = 2$, $\alpha = 5/3$, $n_0 = 11$, $\gamma = 10^4$, $\epsilon = 10^{-1}$
The Synt 1 sequence reproduces the Kolmogorov inertial range of canonical turbulence, while Synt 2 reproduces both the inertial and the dissipative part of the spectrum.

- Synthetic data are scaled on a 180 days time grid ($\Delta t = 100\ s$, $n_{tot} = 155520$)
- 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



Effect of no/linear interpolation on Synt 2 data



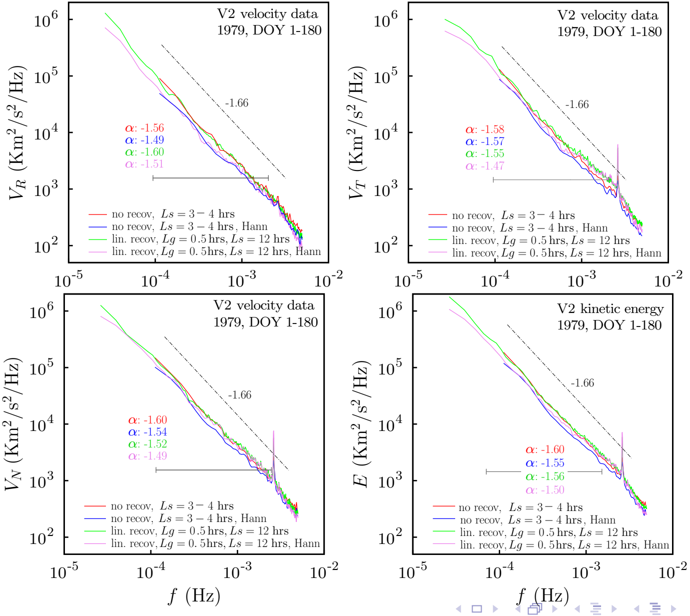
- Effect of segmentation: increase in slope of about 5% in the inertial range .
- Effect of linear interpolation: function of L_g (length of "filled" gaps). This interpolation transfers energy to the low frequences, resulting in an increase (about 6%) in the slope, especially in the high-frequency range ($f > 10^{-3}$Hz).

Effect of no/linear interpolation on Synt 2 data

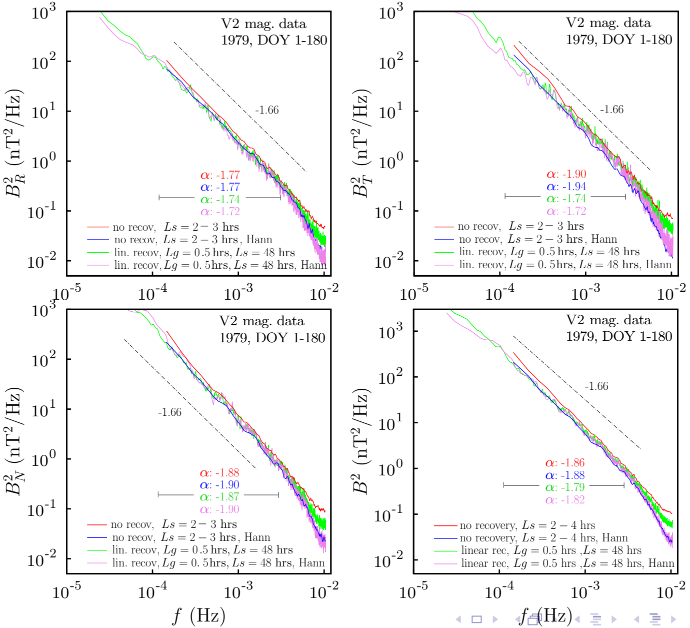
- Effect of windowing: the Hann window function allows to eliminate spurious energy due to discontinuities ($\approx 1/f$) at the boundary of each segment. The effect is minimal at low wavenumbers. In the high-frequency range, on the one hand a significant increase (up to 23%) of the slope is found to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



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



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):

  $\boldsymbol{y} = \boldsymbol{s} + \boldsymbol{n}$ irreg. spaced vector data with errors $\boldsymbol{n}$

  $s^* = \sum_{i=1}^{M} d_{*i} y_i + x_*$ s^* =true value at a particular point

  $\hat{s^*} = \mathbf{S}^T [\mathbf{S} + \mathbf{N}]^{-1} \mathbf{y}$ $\hat{s^*}$ =min. variance estimate for s^*

  Assuming stationary process:

  $S_{ij} = \langle s_i s_j \rangle = f(t_i - t_j)$ is the correlation matrix, estimated from data

  $N_{ii} = \langle n_i^2 \rangle$ is the errors diagonal matrix $n_i \rightarrow \infty$ in "new" points

  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:

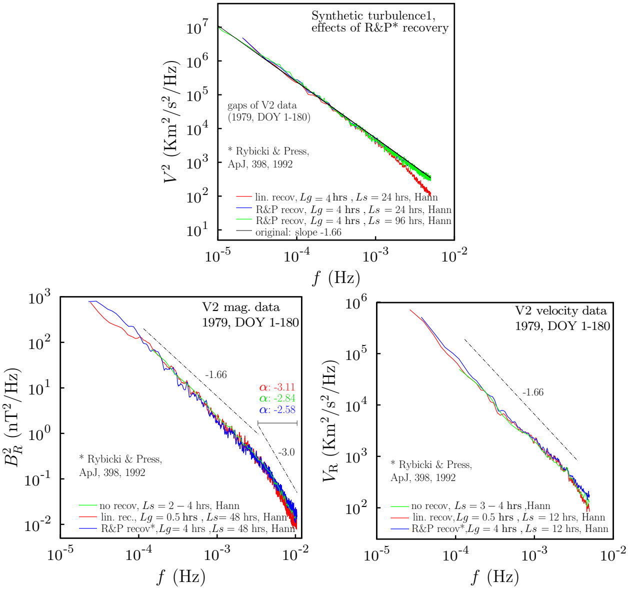
  $s_* = u_* + \hat{s_*}$

  If realizations constrained to data are desired:

  $\boldsymbol{u} = \boldsymbol{V} diag(\lambda_1^{1/2}, ..., \lambda_M^{1/2}) \boldsymbol{r}$ where

  $\lambda_i = eig(\boldsymbol{Q}), \quad \boldsymbol{Q} = [\boldsymbol{S}^{-1} + \boldsymbol{N}^{-1}]^{-1}, \quad \boldsymbol{r} = rand(\mu = 0, \sigma^2 = 1)$

R&P reconstruction



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.