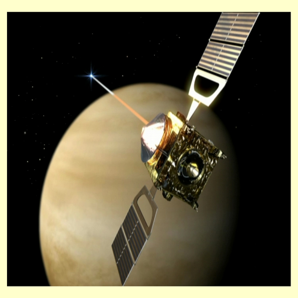
# Solar wind turbulence at 0.72 AU and the response of the Venus magnetosheath



Eliza Teodorescu (1), Marius Echim (1,2), Costel Munteanu (1,3,4), Tielong Zhang (5), Stanislav Barabash (6), Elena Budnik (7), and Andrei Fedorov (7)

(1) Institute of Space Science, Magurele-Bucharest, Romania (eliteo@spacescience.ro), (2) Belgian Institute for Space Aeronomy, Bruxelles, Belgium, (3) University of Bucharest, Magurele, Romania, (4) University of Oulu, Oulu, Finland, (5) Space Research Institute, Graz, Austria, (6) Institute of Space Physics, Kiruna, Sweden, (7) Research Institute in Astrophysics and Planetology, Toulouse, France

## Purpose

Study of solar system plasma turbulence through a widely known and well established collection of analysis methods, starting from simple and progressing to increasing degree of complexity

Systematic study
- catalog of power spectral densities (PSD) for the solar wind magnetic field in the vicinity of Venus (0.72 AU from the Sun)
- catalog of Probabilty Density Functions (PDF) for the solar wind magnetic field around Venus

Statistical study
- behavior of spectral index

## Analyzed data

Unique set of measurements from **Venus Express (VEX)**, which is one of the core missions of the **FP7-STORM project**, Solar system plasma Turbulence: Observations, inteRmittency and Multifractals. VEX is first ESA mission to Venus. The probe orbits Venus once a day in a quasi-polar and eccentrically orbit: between 250 and 66000km from pericenter to apocenter. The data we analyze in the present study were recorded in the time period 2007 - 2009 (STORM data base - D3MINSW).

All results (daily power spectra and probability density functions in the time interval 2007-2008) and analyzed data are available on STORM project site: **http://www.storm-fp7.eu/**

The data are available at:
- ESA's Planetary Science Archive ESA-PSA (http://www.rssd.esa.int/)
- French Automated Data Base Analysis (AMDA) (http://amda.cdpp.eu)

Relevant instruments for our analysis:
- **ASPERA** (Analyser of Space Plasma and Energetic Atoms): electron and ion spectra, their moments (density, temperature, **velocity**) (Barabash et al., 2007)
- **VEX-MAG** (Venus Express Magnetometer): **magnetic field** and position of the spacecraft (Zhang et al., 2006)

## Technique and methodology

**Challenge** Perform **AUTOMATIC ANALYSIS** on day-by-day data files

**Catalog of PSD or PDF (for one year) is obtained after a single run of the code**

Scripting done in **Python:** modular programming language (possibility to add different modules)

Identify time intervals when VEX is in the solar wind using information provided by ASPERA instrument through AMDA interface and generate time tables (.txt format) with the identified time intervals. Then, using time tables generated on AMDA we select and analyze magnetic field data at 1 Hz downloaded from ESA-PSA.

### Selection of the plasma data (AMDA)

Discriminate time intervals with fast solar wind

All time intervals (VEX in the solar wind): $R_{VEX}$>50000 km (~8 $R_v$), $v_{tot}$>100 km/s

Time intervals with fast solar wind: $R_{VEX}$>50000 km (~8 $R_v$), $v_{tot}$>450 km/s

### Selection of the magnetic data (ASCII files from ESA-PSA)

**Although we analyze calibrated data at 1 Hz resolution, small data-gaps still populate the data files and we need to deal with uneven spacing of the measurements**

**Disregard**
- **Time series shorter than 1h**
- **Time series with less than 92% data coverage**
- **Visible non-stationary time series**

What to do?

1) limit data-gaps to a maximum of 30 s (@1Hz → 30 consecutive missing measurements) and remove series with more than 8% of data missing from the total length

2) interpolate the data => evenly spaced time series (1 Hz)

### Theoretical aspects on methodology

**PSD**

One common method to estimate the power spectral density is through Discrete Fourier Transform (using Fast Fourier Transform algorithm). PSD is proportional to the squared Fourier coefficients. For a time series: $y(n)=y_1, \ldots, y_N$ the *periodogram* estimates the PSD:

$$P(\omega)=\frac{1}{N}\left|\sum_{n=1}^{N} y_n e^{-j\omega n}\right|^2 = X_c^2(\omega)+X_s^2(\omega)$$

$$\text{where: } X_c(\omega)=\frac{1}{\sqrt{N}}\sum_{n=1}^{N} y_n\cos(\omega n),\; X_s(\omega)=\frac{1}{\sqrt{N}}\sum_{n=1}^{N} y_n\sin(\omega n)$$

**Welch method** – partition y(n) of length N in a set of K **overlapping segments** of length M=N/K and **average periodograms** (Welch P.D. 1967)

**PDF**

Construct incremental measure of turbulent fluctuations based on differences over a range of scales τ=jδ, δ=time resolution of the measurements:

$$\Delta Q^{\tau}(t_i,\tau)=Q(t_i+j\delta)-Q(t_i),\quad i=1,N-j\delta$$

For each τ we collect the ensemble of differences ($\Delta Q^{(\tau)}$), compute the histogram and normalize all histograms to obtain the Probability Density Function (PDF).

A quantitative measure of intermittency is the forth order moment of the PDF, the flatness:

$$F=\frac{\langle \Delta P(t,\tau)^4\rangle}{\left(\langle \Delta P(t,\tau)^2\rangle\right)^2}$$

This parameter is equal to 3 for Gaussian fluctuations

## Systematic Study

For all time intervals which passed the selection criteria for the time period 2007-2009:

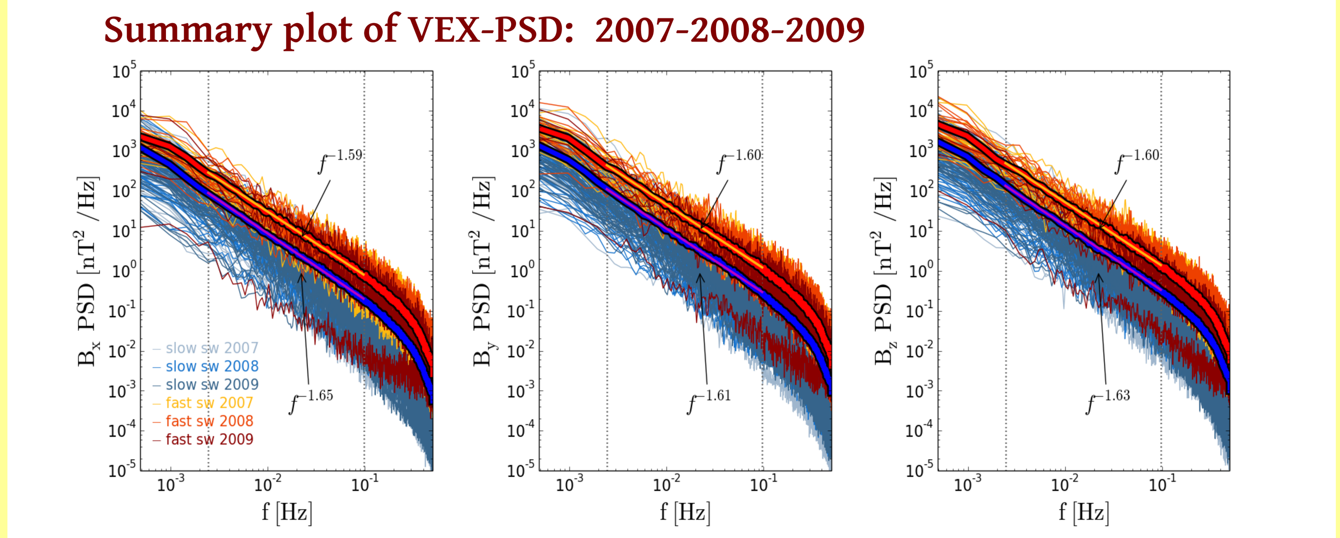
▶ **Compute PSDs** using a fixed segment length (~35 min), 90% overlap between segments and Hanning window as input parameters for Welch algorithm. We evaluate 4 configurations: data with gaps (<30s) or interpolated data (either not-normalized or normalized)

We estimate the spectral index through a least_squares linear fit in log-log scale between the frequencies marked by the dashed lines in the plot below. This procedure is also automatically applied to all individual power spectra.

**Time series Summary:**
2007: 49 slow sw, 23 fast sw
2008: 58 slow sw, 18 fast sw
2009: 49 slow sw, 7 fast sw

**Grouped in sets:** $(B_x, B_y, B_z)$, $(B, B^2)$, $(B_\parallel, B_\perp)$

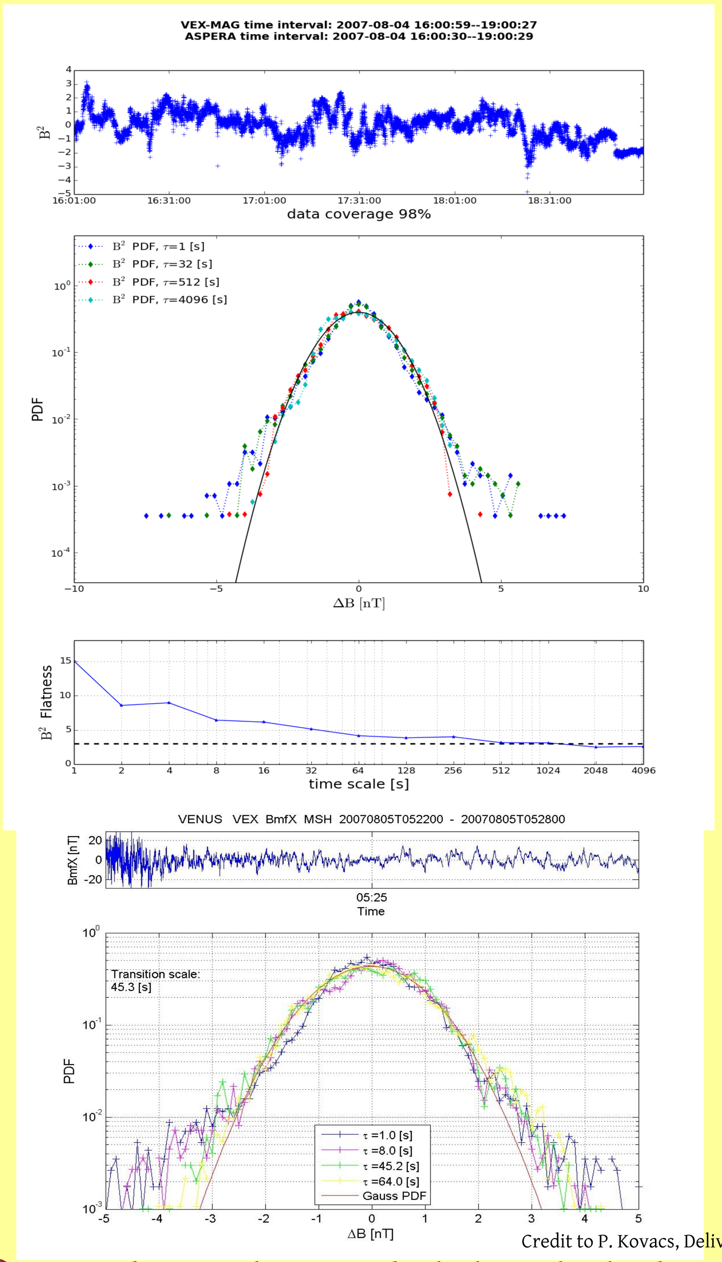
**Summary plot of VEX-PSD: 2007-2008-2009**

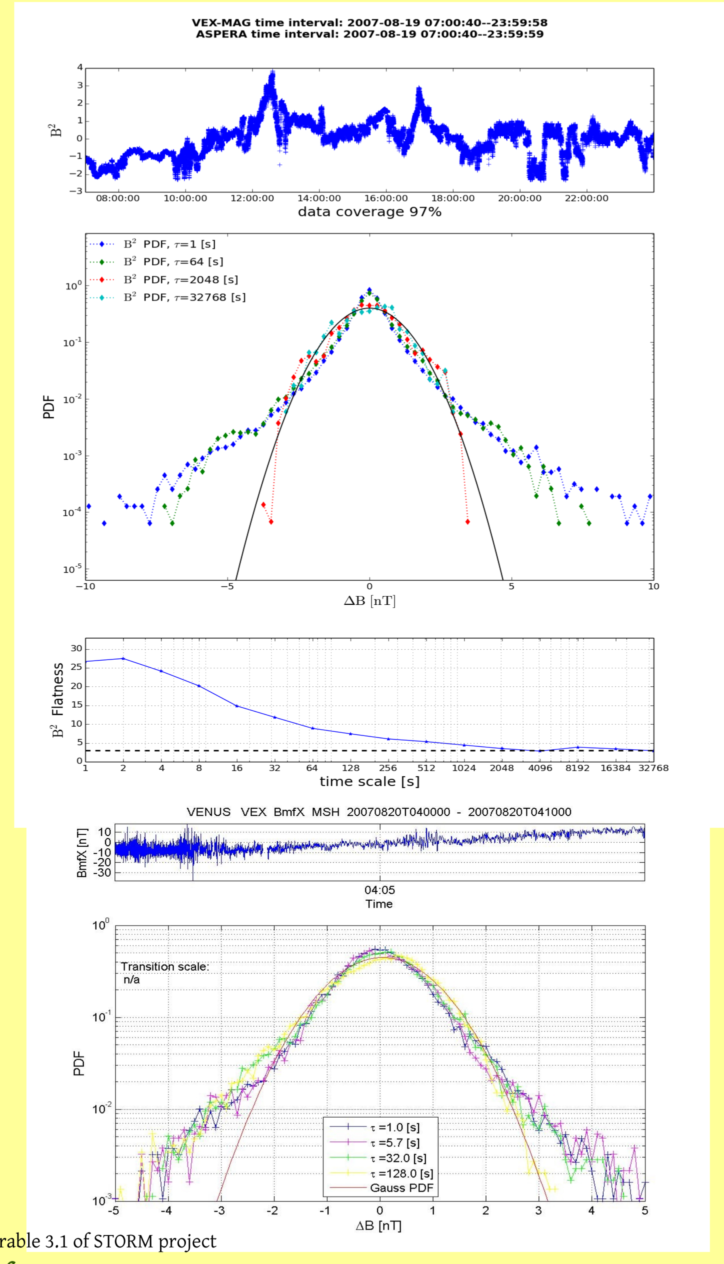


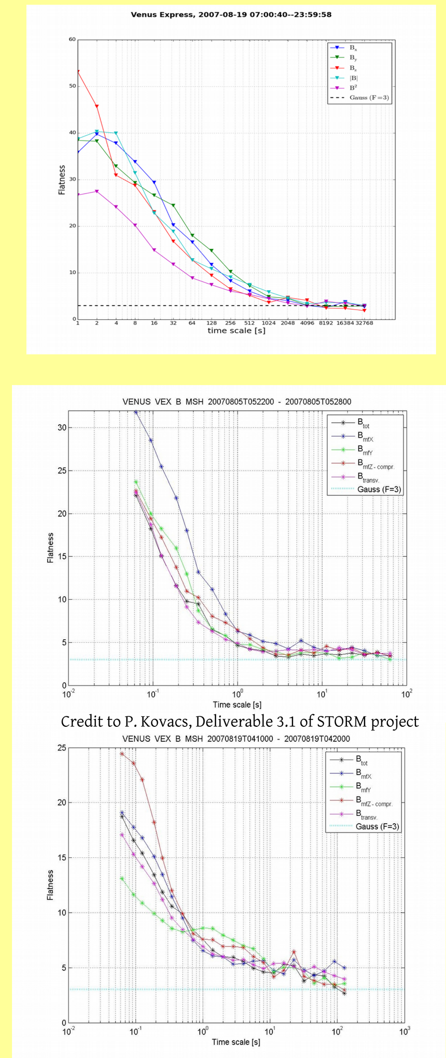

▶ **Compute PDFs** for the original time series, normalized, with data coverage higher than 92%

**Grouped in sets:** $(B_x, B_y, B_z)$, $(B, B^2)$

**Time Series Summary:**
2007: 152 slow sw, 96 fast sw
2008: 183 slow sw, 63 fast sw



Credit to P. Kovacs, Deliverable 3.1 of STORM project

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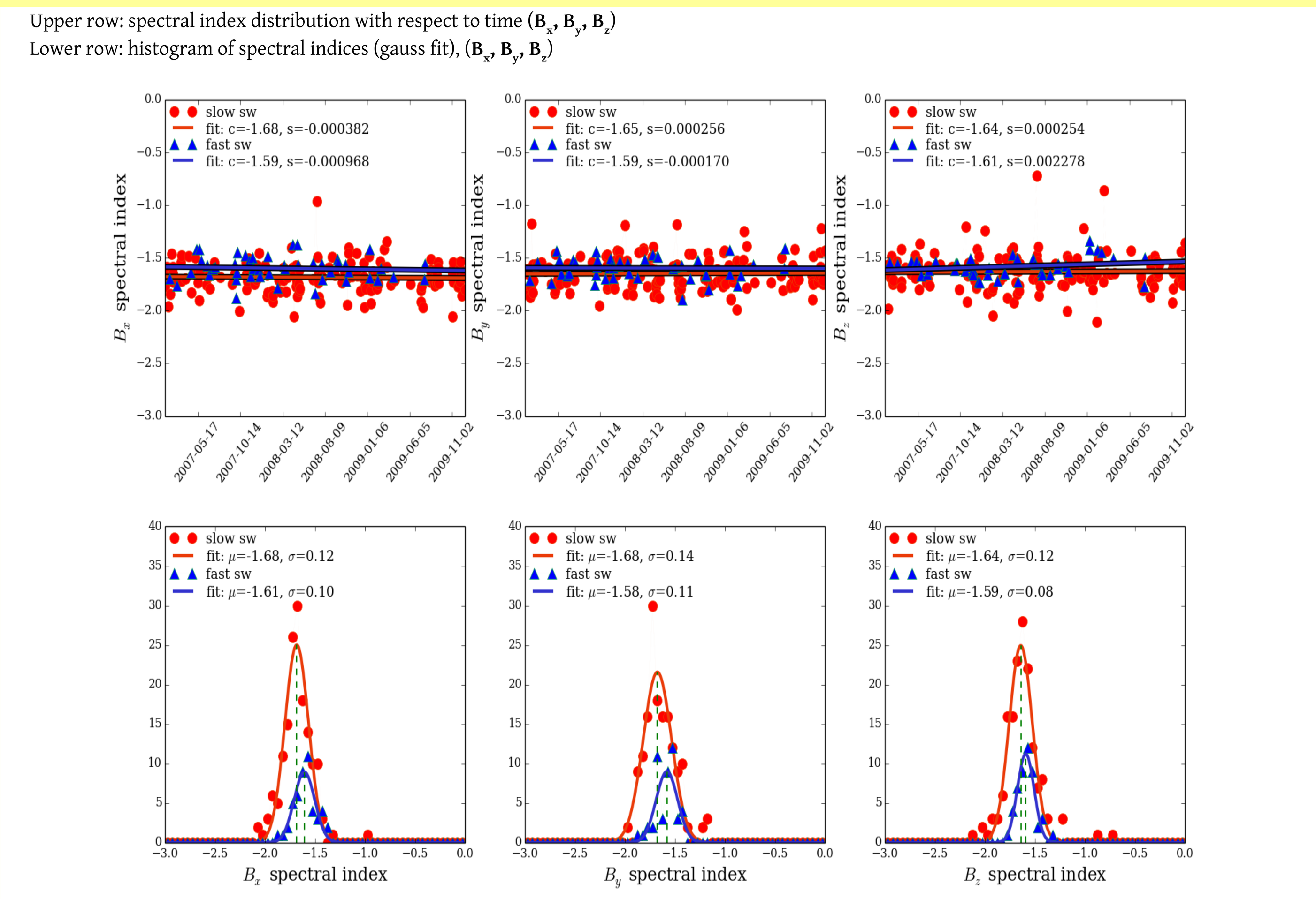
▶ **PSD and PDF Results** are saved in both: graphical and ASCII format

## Statistical study

For each time interval we estimate the power spectral density which exhibits a power-low behavior. We apply a linear fit in log-log scale and calculate the spectral index of each PSD. We investigate the behavior of the spectral indices over time (2007-2009) (upper row in the plot below). A linear fit indicates the variation of spectral indices over time. The lower row of plots indicates that the spectral indices fit Gaussian distributions with mean values between -5/3 ("Kolmogorov -5/3 spectrum" (1941)) and -2 (Goldreich and Sridhar, 1995). Systematically, slow solar wind is characterized by steeper slopes.

Upper row: spectral index distribution with respect to time $(B_x, B_y, B_z)$
Lower row: histogram of spectral indices (gauss fit), $(B_x, B_y, B_z)$

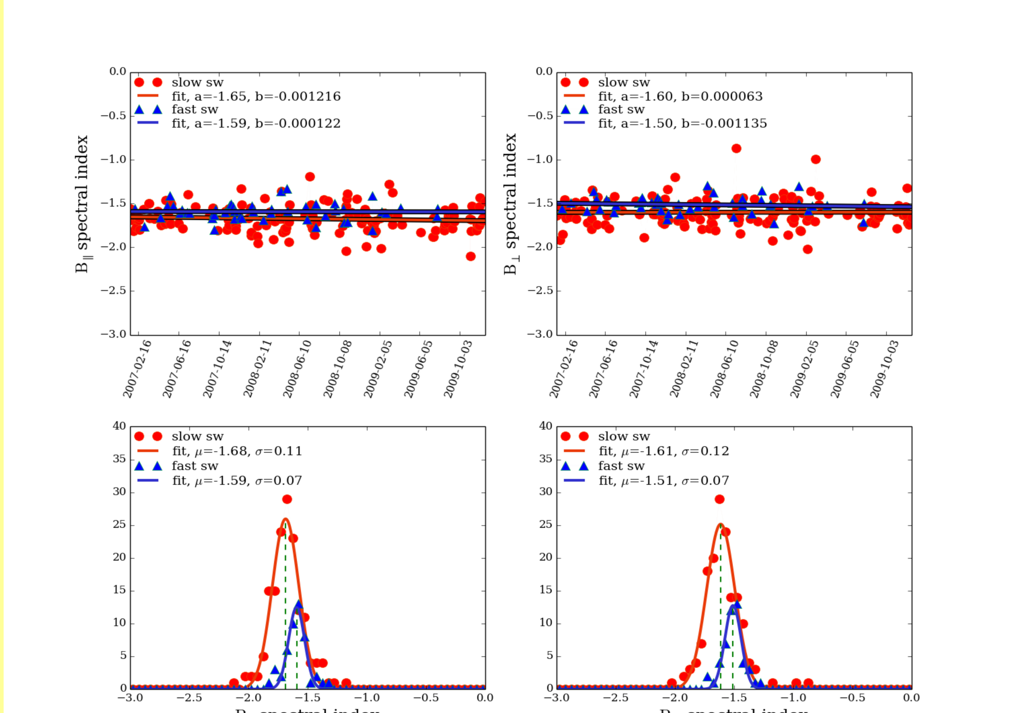



**Parallel** and **perpendicular** components of the magnetic field are calculated with respect to the **mean** magnetic field (calculated as the mean of the magnetic field measurements in the time interval considered for each PSD estimation):

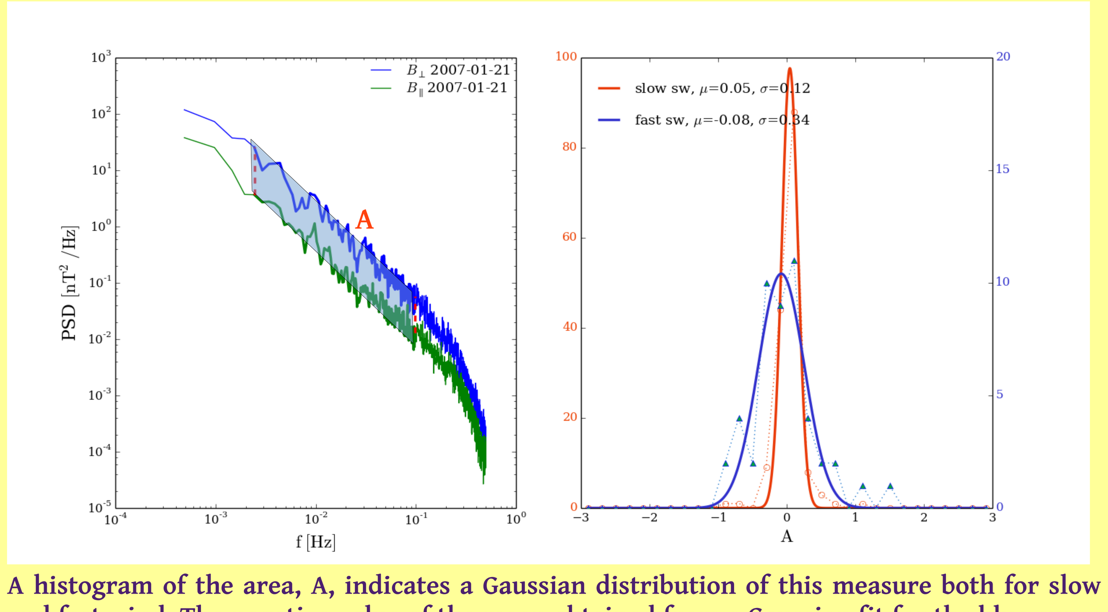
$$\vec{B}\cdot\langle\vec{B}\rangle = B\cdot\langle B\rangle\cos\alpha = B_x\cdot\langle B_x\rangle + B_y\cdot\langle B_y\rangle + B_z\cdot\langle B_z\rangle$$

$$\text{when } \alpha=0^0 \quad B_\parallel=\frac{B_x\cdot\langle B_x\rangle + B_y\cdot\langle B_y\rangle + B_z\cdot\langle B_z\rangle}{\sqrt{\langle B_x\rangle^2+\langle B_y\rangle^2+\langle B_z\rangle^2}}$$

$$B_\perp=\sqrt{B^2-B_\parallel^2}$$




**The difference between the power content of parallel and perpendicular magnetic field components is quantified through the magnitude of the area between the respective PSD curves (as shown in the figure below) computed as the difference:** $A=\int PSD(B_\perp)df-\int PSD(B_\parallel)df$




**A histogram of the area, A, indicates a Gaussian distribution of this measure both for slow and fast wind. The negative value of the mean obtained from a Gaussian fit for the blue curve seems to suggest that more power flows on the parallel component for the fast solar wind.**

## Summary and Conclusions

- **Catalog of PSDs - created for 2007, 2008 and 2009 for $(B_x, B_y, B_z)$, $(B, B^2)$, $(B_\parallel, B_\perp)$**
  - Welch algorithm: data with gaps and interpolated (normalized and not-normalized signal):
    - 2007: 72 time intervals (23 are fast solar wind)
    - 2008: 76 time intervals (18 are fast solar wind)
    - 2009: 56 time intervals ( 7 are fast solar wind)
- **Catalog of PDFs - created for 2007 and 2008 for $(B_x, B_y, B_z)$, $(B, B^2)$**
  - 2007: 248 time intervals (96 are fast solar wind)
  - 2008: 246 time intervals (63 are fast solar wind)
  - The Flatness for all magnetic field components has also been computed at all time scales considered for the present analysis
- **Global behavior of PSD – summary plot of PSD**
  - power law regime observed in the frequency range [$10^{-3}$ Hz, $10^{-1}$ Hz] (corresponding to the smallest scales of the solar wind inertial range)
  - power over all frequencies is larger for fast streams
  - visible spectral break in the PSD at ~2*$10^{-1}$ Hz
- **Spectral indices computed for all PSD**
  - variation of spectral indices with time (linear fit)
  - distribution of spectral indices (gaussian fit)
    - Slow solar wind has steeper slope
- **Measure of power difference between perpendicular and parallel components of the magnetic field**
  - For fast solar wind, the parallel component of the magnetic field seems to contain more power than the perpendicular component (negative A)

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**References:**

Barabash, S., J.-A. Sauvaud, H. Gunell, et al., The Analyser of Space Plasmas and Energetic Atoms (ASPERA-4) for the Venus Express mission, Planetary and Space Science 55, 1772–1792, 2007

Golreich P., Sridhar S., Towards a theory of interstellar turbulence. 2: Strong Alfvenic tubulence, The Astrophysical Journal, 438, 763-775, 1995

Kolmogorov, A. N. "The local structure of turbulence in incompressible viscous fluid for very large Reynolds numbers" (1941). translated in English by V. Levin, Proceedings of the Royal Society A 434 (1991): 9–13

Kolmogorov, A. N. "The local structure of turbulence in incompressible viscous fluid for very large Reynolds numbers" (1941). translated in English by A.N. Kolmogorov, Proceedings of the Royal Society A 434 (1980): 15–17

Morley S.K., Koller J., Welling D.T., Larsen B.A., Henderson M.G., Niehof J.T., *Spacepy - A Python-based library of tools for the space sciences*, Proceedings of the 9th Python in science conference (SciPy 2010), 2011, Austin, TX

Welch, P.D., The Use of Fast Fourier Transform for the Estimation of Power Spectra: A Method Based on Time Averaging Over Short, Modified Periodograms, IEEE Trans. Audio Electroacoustics, AU-15, 70, 1967

Zhang, T., Baumjohann, W., Delva, M., et al., Magnetic field investigation of the Venus plasma environment: Expected new results from Venus Express, Planetary and Space Science 54, 1336–1343, 2006