Using a shell turbulence model to describe the evolution of the solar wind spectrum

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Formulation of the problem

- Solar wind is a characteristically turbulent medium with an emerging turbulence cascade from subionic to interplanetary scales.
- In our paper we try to answer the questions to what the extend the evolution of solar wind energy spectrum can be described within free MHD devolution.
- Using data from the Parker Solar Probe satellite mission, we collect spectral characteristics of the near-Sun plasma and run them through the ***shell MHD-model*** and compare them with available near-Earth ones.
- The main attention is paid to the magnetohydrodynamic part (before so-called subionic break in the spectrum), for which we analyse energy dissipation, the behaviour of the spectrum slope and the movement of a large-spectrum break forming during the formation of the cascade.

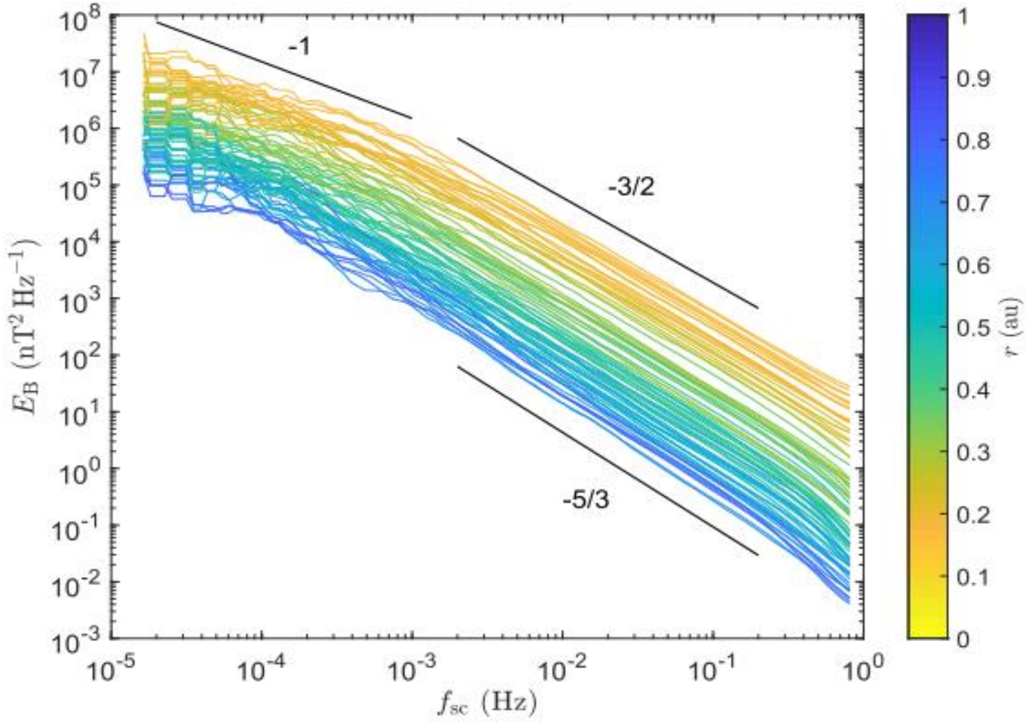
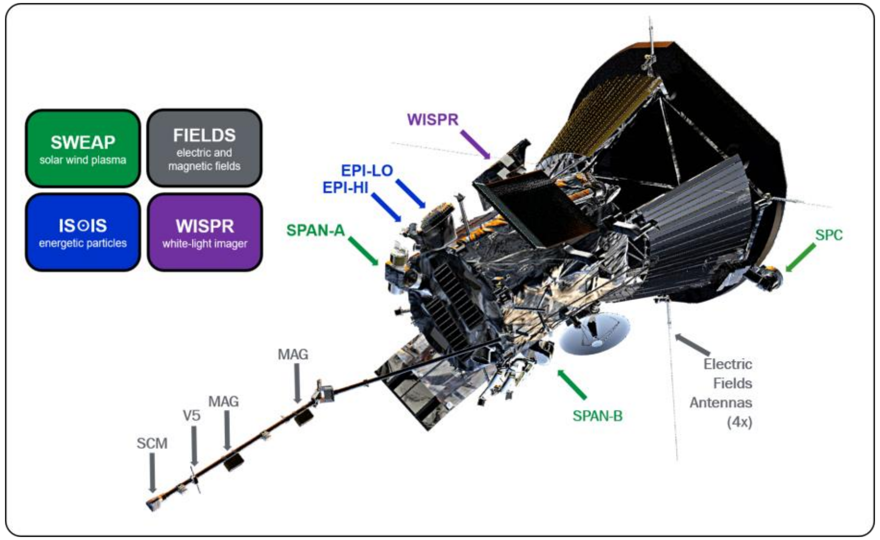


Figure 1. Magnetic field power spectrum, E_B, at different heliocentric distances, r, over the first two *PSP* orbits. Several power-law slopes are marked for comparison. A turbulent inertial range is present at all distances, with a flattening at low frequencies. Deviations at high frequencies ($f_{sc} \gtrsim 0.3$ Hz) are partly due to digital filter effects.

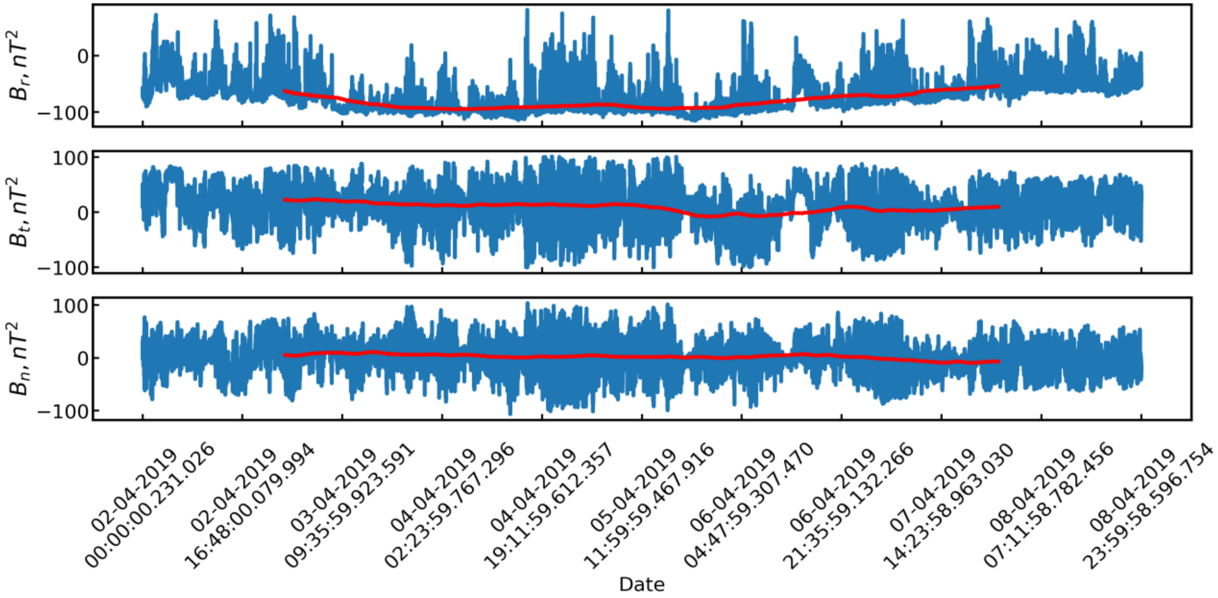
2020, AJSS, Chen et al.

Experimental data

- The input data for the shell MHD-model are the energy spectra of magnetic and ion's velocity field. We reconstruct these spectra using data from PSP satellite mission; the daily average is subtracted from the weekly series by moving average, and the stochastic stationarity of the random series is checked.



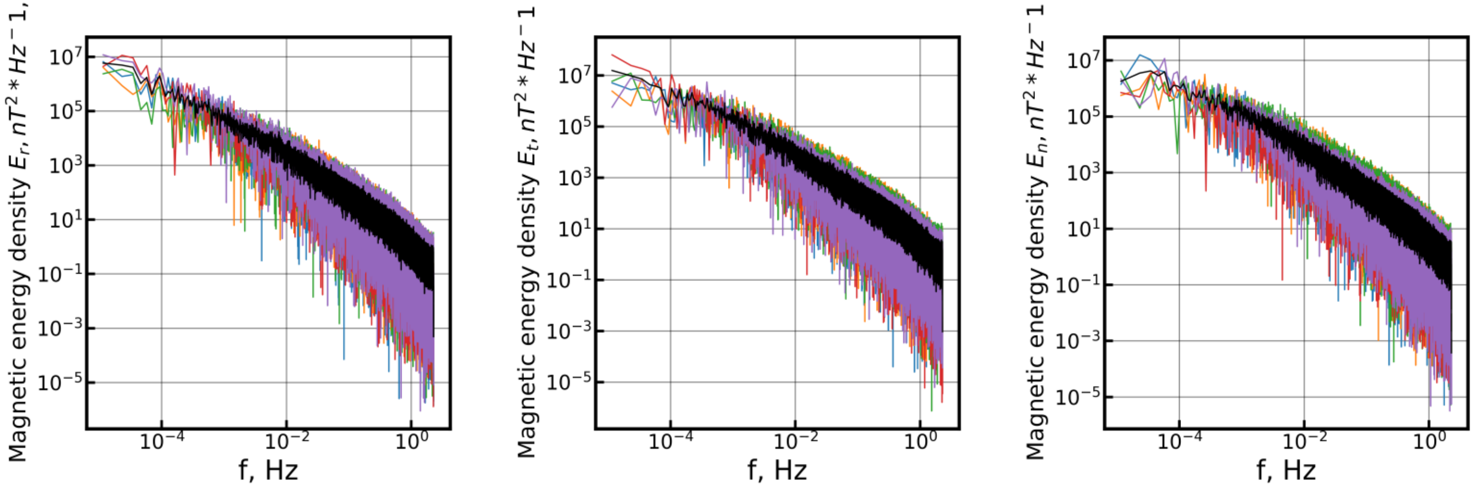
PSP satellite with its sensors used in the paper

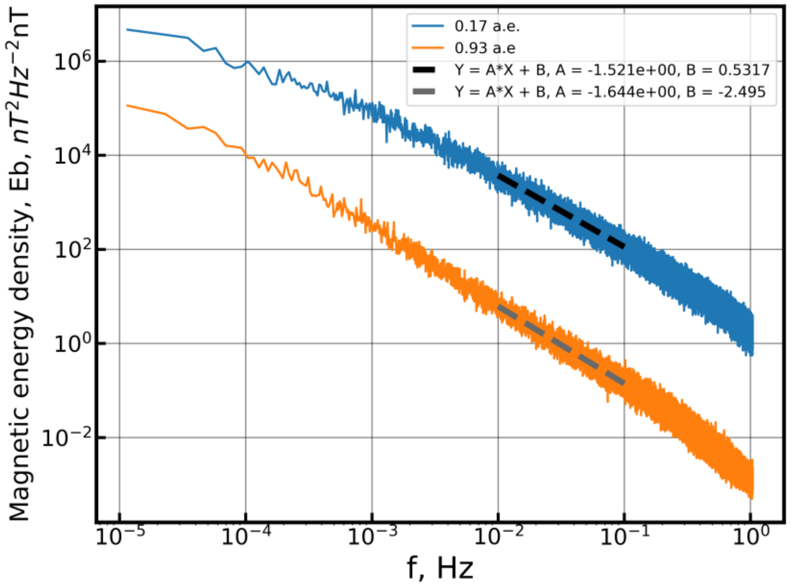


The weekly series B(t) with daily moving average

Spectral energy density

- The experimental data corresponded to weekly observation. We can divide the period under study into days and apply Fourier transform to fluctuation of field projection.
- The spectral density reconstruction scheme described above is used for two satellite positions: near the Sun and at a huge distance from it.





Calculated fluctuation spectra.
The right figure is a full spectrum for the absolute value of magnetic induction.

Shell model

- One of the simplest models of overgrown turbulence are the shell models. These models take into account standard three-dimensional MHD conservation laws and assume that turbulence is isotropic. They rewrite original MHD dimensional system of equations in Fourie representation and approximate nonlinear terms of it using a finite polynomial series.

$$\partial_t \mathbf{v} + (\mathbf{v}\nabla)\mathbf{v} - (\mathbf{B}\nabla\mathbf{B}) = -\nabla(P + B^2/2) + R^{-1}\Delta\mathbf{v}$$

$$\partial_t \mathbf{B} + (\mathbf{v}\nabla)\mathbf{B} - (\mathbf{B}\nabla)\mathbf{v} = \mathrm{Rm}^{-1}\nabla\mathbf{B}$$

$$\nabla\mathbf{v} = 0$$

$$\nabla\mathbf{B} = 0$$

- Shell model approximation

$$\frac{dU_n}{dt} = W_n(\mathbf{U},\mathbf{U}) - W_n(\mathbf{B},\mathbf{B}) - \frac{k_n^2}{\mathrm{R}} U_n,$$

$$\frac{dB_n}{dt} = W_n(\mathbf{U},\mathbf{B}) - W_n(\mathbf{B},\mathbf{U}) - \frac{k_n^2}{\mathrm{Rm}} B_n,$$

$$U_n = a_n + ib_n,\ B_n = c_n + id_n,$$

$[k_n, k_{n+1}]$, where is $k_n = q^n$ is a width of the selected interval

$$H_B = i\sum k_n^{-1}((B_n^*)^2 - B_n^2)/4 = \sum k_n^{-1} c_n d_n,$$

$$H_C = i\sum (U_n B_n^* + U_n^* B_n)/2 = \sum (a_n c_n + b_n + d_n),$$

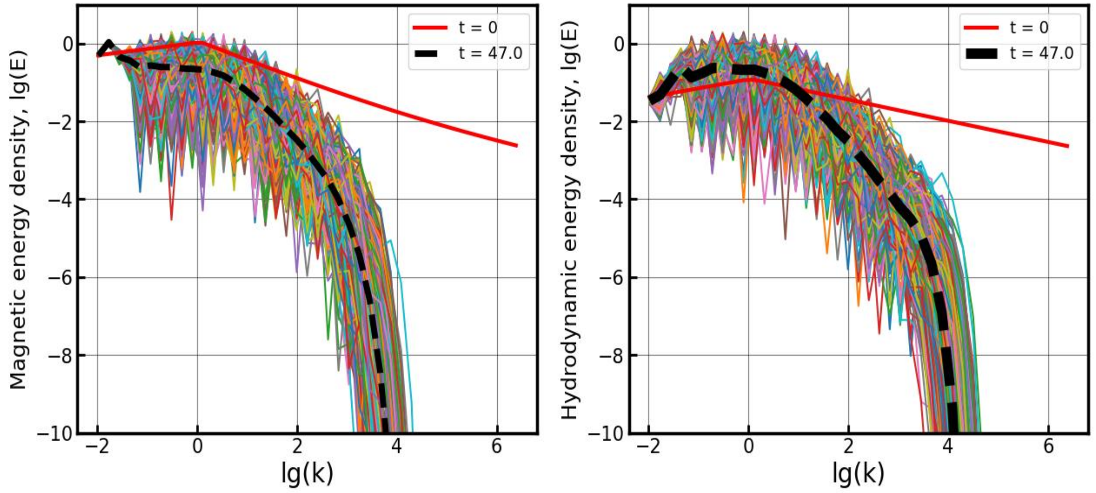
$$E = \sum (|U_n|^2 + |B_n|^2)/2$$

Numerical implementation

- The form of the nonlinear terms W is determined by conservation laws (in the non-dissipative approximation), which in our case are given by the formulas.

$$
\begin{aligned}
W_n(\mathbf{X},\mathbf{Y}) = ik_n[&(X_{n-1}Y_{n-1} + X^*_{n-1}Y^*_{n-1}) - \lambda X^*_n Y^*_{n+1} \\
&-\frac{\lambda^2}{2}(X_nY_{n+1} + X_{n+1}Y_n + X_nY^*_{n+1} + X^*_{n+1}Y_n) \\
&-\frac{\lambda}{2}(X^*_{n-1}Y_{n-1} - X_{n-1}Y^*_{n-1}) + \lambda X^* Y_{n+1}] \\
&-ik_n\lambda^{-5/2}[\frac{1}{2}(X_{n-1}Y_n + X_nY_{n-1}) + \lambda X^*_nY^*_{n-1} \\
&-\lambda^2(X_{n+1}Y_{n+1} + X^*_{n+1}Y^*_{n+1}) + \frac{1}{2}(X_nY^*_{n-1} + X^*_{n-1}Y_n) \\
&-\lambda X^*_nY_{n-1} + \frac{\lambda}{2}(X^*_{n+1}Y_{n+1} - X_{n+1}Y^*_{n+1})].
\end{aligned}
$$

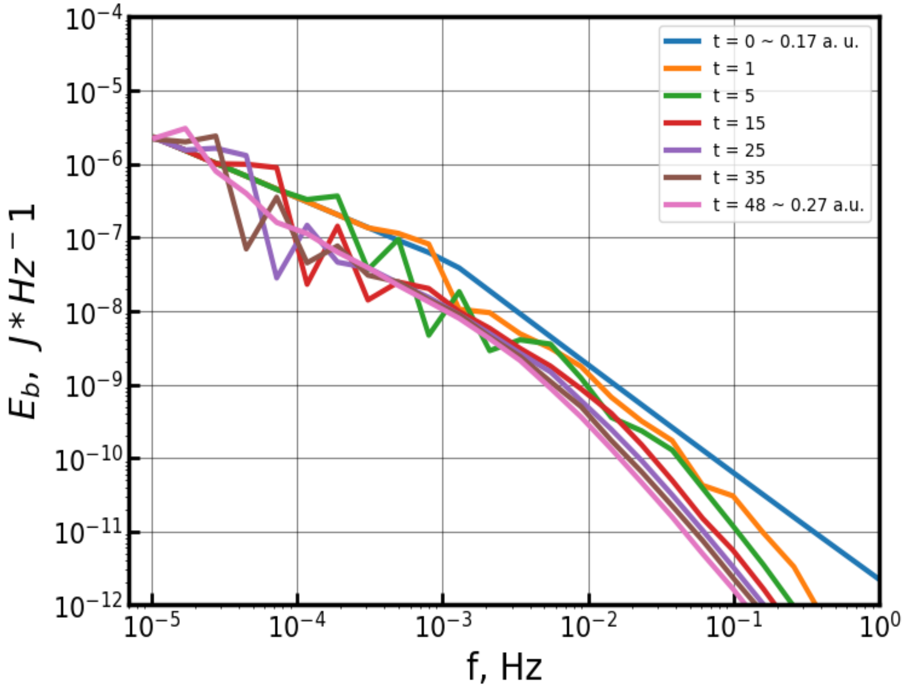
- The key numerical method in this paper is the Runge-Kutta fourth-order method. The evolution of spectrum is calculated by parallel programming in 1024 processes.



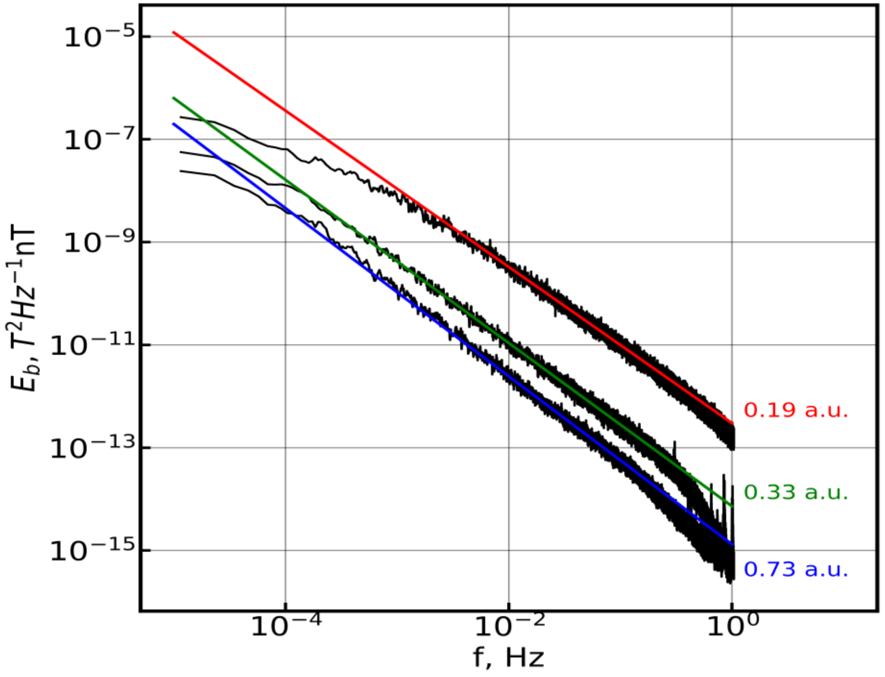
Averaging over 1024 parallel processes for modeling spectrum evolution. There is dimensional time in the legend to the graph.

Comparison of model and experiment

- Dimensionless experimental spectra as input to the cascade model. The results of free MHD-devolution simulation are comparing with experimental ones. The comparison is carried out both at qualitative level and in dimensionless and dimensional forms.



Model spectra for distances from 0.17 to 0.27 a. u.



The real spectra for three heliocentric distances

Conclusion and the future ideas

- Data from PSP satellite mission to gather the magnetic and velocity fields of solar wind plasma in the near-Sun space and near-Earth one was collected and processed. The processed data made it possible to reconstruct hydrodynamic and magnetic spectral density of fluctuations, as well as confirm previously known data on the dynamics of the solar wind energy spectra. The paper attempted to explain behaviour of the large-scale part of fluctuation spectrum due to free devolution of isotropic three-dimensional MHD turbulence.
- Free devolution simulated within MHD-shell approach, the input data for which were experimental PSP data on energy spectra of fluctuations. Particular attention was paid to the large-scale break on the left end of the inertial interval.
- Shell modelling withing the shell approach showed to us the fundamental possibility of describing the behaviour of that break. Also, it demonstrated a drop in the amplitude of the fluctuation power, smoothing of the spectrum, conservation of the inertial interval and movement of the initially specified left-side break towards even larger scales.
- However, the difference between experimental and numerical results demonstrates the problem of describing the movement of the named spectrum marker due to only free MHD-devolution. It is supposed to get greater similarity of ones in further research by abandoning the idea of exclusively free devolution and allowing for external influence like pumping up of energy or helicity near the large-scale break.

Approbation of results

- XXX International Scientific Conference of Students, Postgraduate Students and Young Scientists “Lomonosov-2023”. Section “Physics”, Moscow, Russia, April 10-21, 2023. Дуканов И. А., Юшков Е. В., Соколов Д. Д. - Использование оболочечной модели для описания турбулентности солнечного ветра.
- XX Conference of Young Scientists “Fundamental and Applied Space Research”, Space Research Institute RAS, Russia, April 12-14, 2023. Дуканов И. А., Юшков Е. В., Соколов Д. Д. - Описание турбулентного каскада солнечного ветра в рамках оболочечного подхода.
- Conference "Problems of Cosmophysics" named after. Panasyuk M.I., Branch of Lomonosov Moscow State University in Dubna, July 10-13, 2023. Дуканов И. А., Юшков Е. В., Соколов Д. Д. - Эволюция энергетического спектра солнечного ветра в рамках каскадного приближения.

Thank you for your attention!

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