Proton energy spectra of energetic storm particle events and their relation with magnetic field turbulent fluctuations nearby the associated interplanetary shocks

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1. Context and motivation

- In the framework of the project Comprehensive spAce wEather Studies for the ASPIS prototype Realization (CAESAR), we studied several Energetic Storm Particle (ESP) events observed by various spacecraft (S/C).
- We analysed the ESP proton energy spectra, as they provide useful information for the investigation of the acceleration mechanisms occurring at interplanetary (IP) shocks.
- The turbulent magnetic field fluctuations in the upstream and downstream regions of the shocks were also investigated.
- Here, we present results concerning two of the investigated ESP events.

2. Spectral shapes and acceleration mechanisms

- We considered the functional forms mentioned below (where E is the particle energy and dJ/dE the differential flux) to fit the ESP proton kinetic energy spectra.

Ellison-Ramaty spectrum (Diffusive shock acceleration)

$$\frac{dJ}{dE} = CE^{-\gamma_a}\exp(-E/E_0)$$

- The diffusive shock acceleration (DSA) theory predicts a power-law energy spectrum, with the spectral index related to the shock compression ratio. Ellison & Ramaty (1985) argued that the power-law spectra should roll over at high energies due to finite size effects and proposed an exponential decay to describe this characteristic.

Double power law spectrum

$$\frac{dJ}{dE} = C\,E^{-\gamma_a}e^{-\left(\frac{E}{E_0}\right)} \quad \text{for } E \leq (\gamma_b-\gamma_a)E_0$$
$$\frac{dJ}{dE} = C\,E^{-\gamma_b}\left\{[(\gamma_b-\gamma_a)E_0]^{(\gamma_b-\gamma_a)}\,e^{(\gamma_a-\gamma_b)}\right\} \quad \text{for } E \geq (\gamma_b-\gamma_a)E_0$$

- The double-power-law representation of Band et al. (1993) was proposed in some works (see e.g. Mewaldt et al 2005) to provide better fits than the Ellison-Ramaty function to SEP particle energy spectra.
- The presence of the spectral break has been attributed to processes able to modify the power-law spectral form produced by the DSA, such as stochastic reacceleration in enhanced Alfvénic downstream turbulence.

Weibull spectrum

$$\frac{dJ}{dE} = C\left(\frac{E}{E_\tau}\right)^{\gamma-1}E^{1/2}\exp\left[-\left(\frac{E}{E_\tau}\right)^{\gamma}\right]$$

- The Weibull distribution was found to provide the best fit for the particle energy spectrum in several SEP and ESP events (see e.g. Laurenza et al. 2015; Chiappetta et al. 2021).
- The Weibull spectrum can be obtained as a steady-state solution of the diffusion-loss equation in a model wherein acceleration is represented as an anomalous diffusion in momentum space (Pallocchia et al. 2017). In this framework, the Weibull spectrum can be related either to stochastic acceleration (SA) or to shock surfing acceleration (SSA). In the latter case the expected value of the Weibull spectral index is $\gamma = 0.5$.

3. Role of the MHD turbulence around the shocks

- The characteristics of MHD turbulence around IP shocks can have a significant impact on particle acceleration processes. A significant correlation between the high energy ion flux and the turbulence level (quantified by the total power of magnetic fluctuations in a given frequency range) in the downstream region was found in some previous works (Claßen et al. 1999; Chiappetta et al. 2021).
- The turbulence properties around IP shocks can be analysed in more detail through the power spectral density (PSD) and structure functions of the magnetic field.
- More specifically, in order to obtain information about the intermittency level of magnetic field fluctuations, we used the flatness (or kurtosis)

$$F_i(\tau) = S_4^{(i)}/[S_2^{(i)}]^2\ ,$$

where $S_p^{(i)}(\tau) = \langle|B_i(t+\tau)-B_i(t)|^p\rangle$ are the structure functions of order p of the magnetic field increments, $B_i(t)$ are the magnetic field components, τ the timescale separation, and $\langle\cdot\rangle$ denotes the time average over the considered interval.

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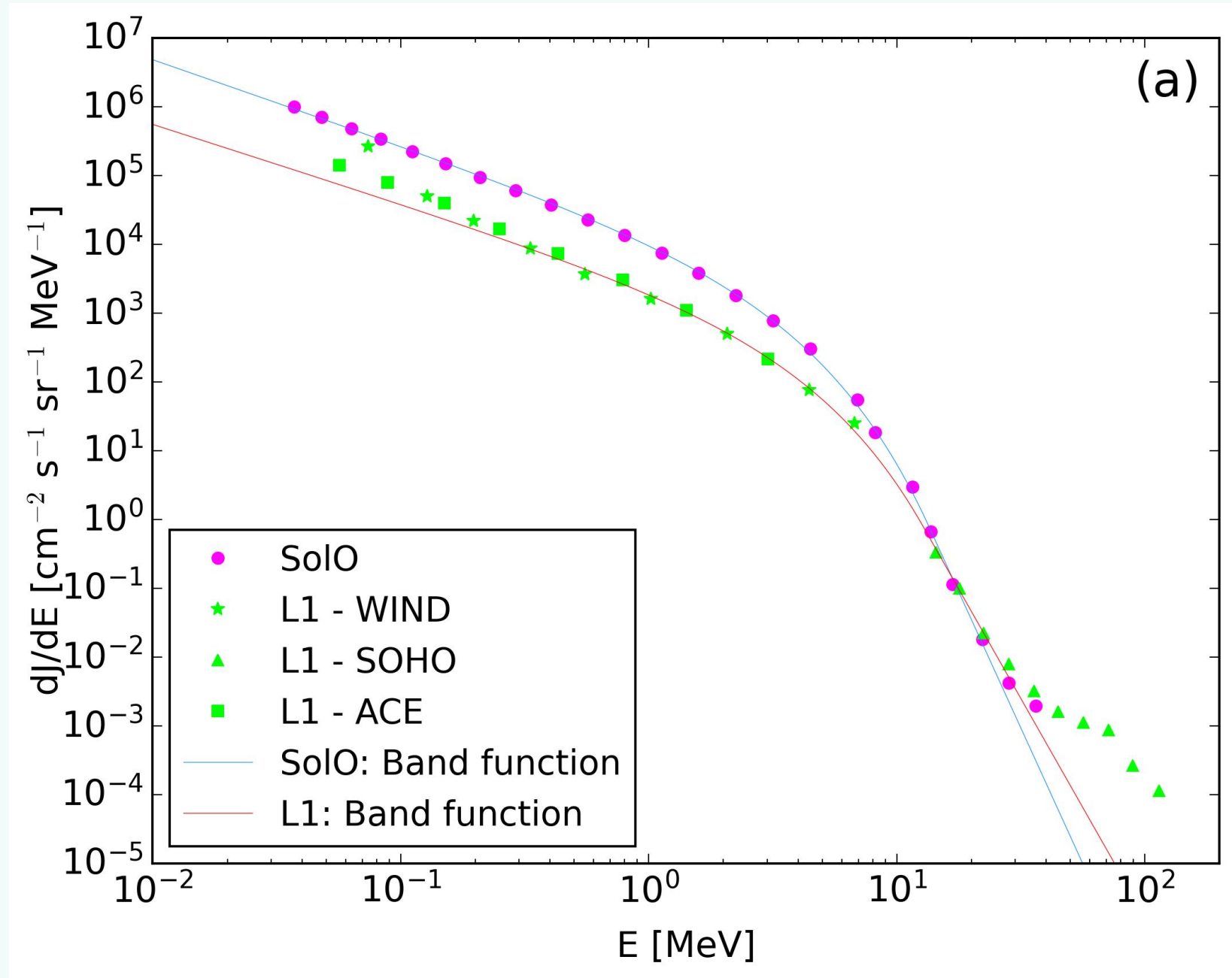
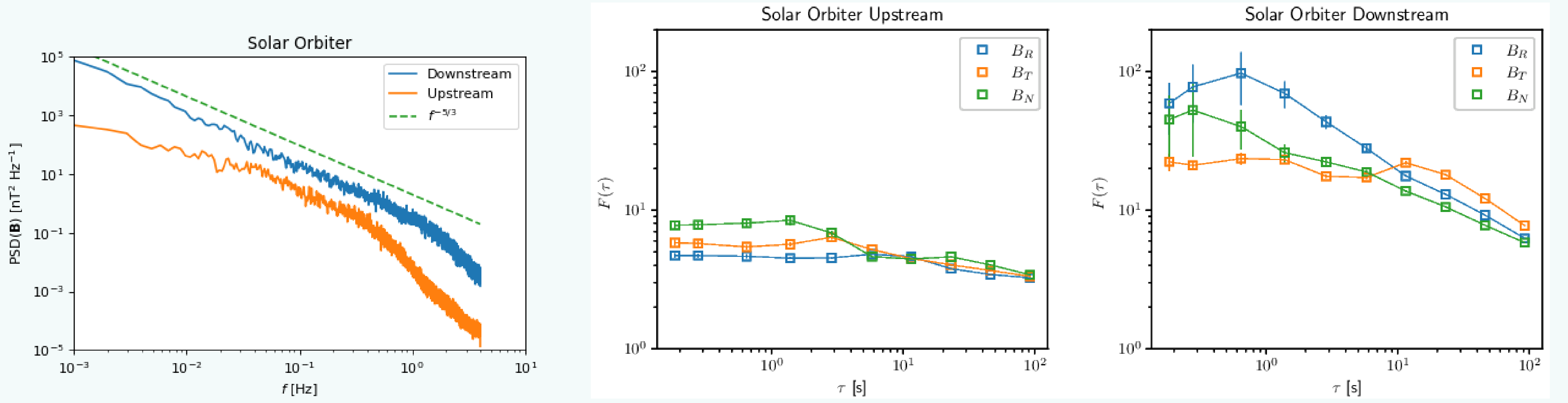
4. The 3 November 2021 ESP Event

- Shock passage at Solar Orbiter (SolO, located at 0.85 AU) at 14:04 UT, and at Wind at 19:35 UT. The main shock parameters (shock-normal angle θ_{Bn}, fast magnetosonic Mach number M_{ms}, compression ratio r, and plasma β), calculated in Trotta at al.(2023), are shown in the table.
- To calculate the proton energy spectrum at SoLO, we took proton flux data from EPT and HET sensors (energy range 40 keV – 82 MeV). For the L1 Lagrangian point, we used data from Wind, ACE and SOHO (energy range 40 keV – 130 MeV, considering all the three S/C), combining the data from the three S/C through a suitable calibration procedure. Both at SoLO and at L1 the flux enhancements are visible up to ≈ 20 MeV.
- The average differential fluxes dJ/dE (fig. on the right) were calculated for both cases over an interval of three hours around the shock arrival. The best fit was obtained with the Band double power law function. The power law indexes are $\gamma_a \approx 1.2$ at low energies in both cases, while at high energies $\gamma_b \approx 7.9$ for SolO and $\gamma_b \approx 6.4$ at L1.

SC	DATE	TIME	θ_{Bn}	r	β	M_{ms}
Solar Orbiter	03/11/2021	14 : 04 UT	45.3°	1.47	0.5	5.5
Wind	03/11/2021	19 : 35 UT	33.1°	5.15	0.4	5.3

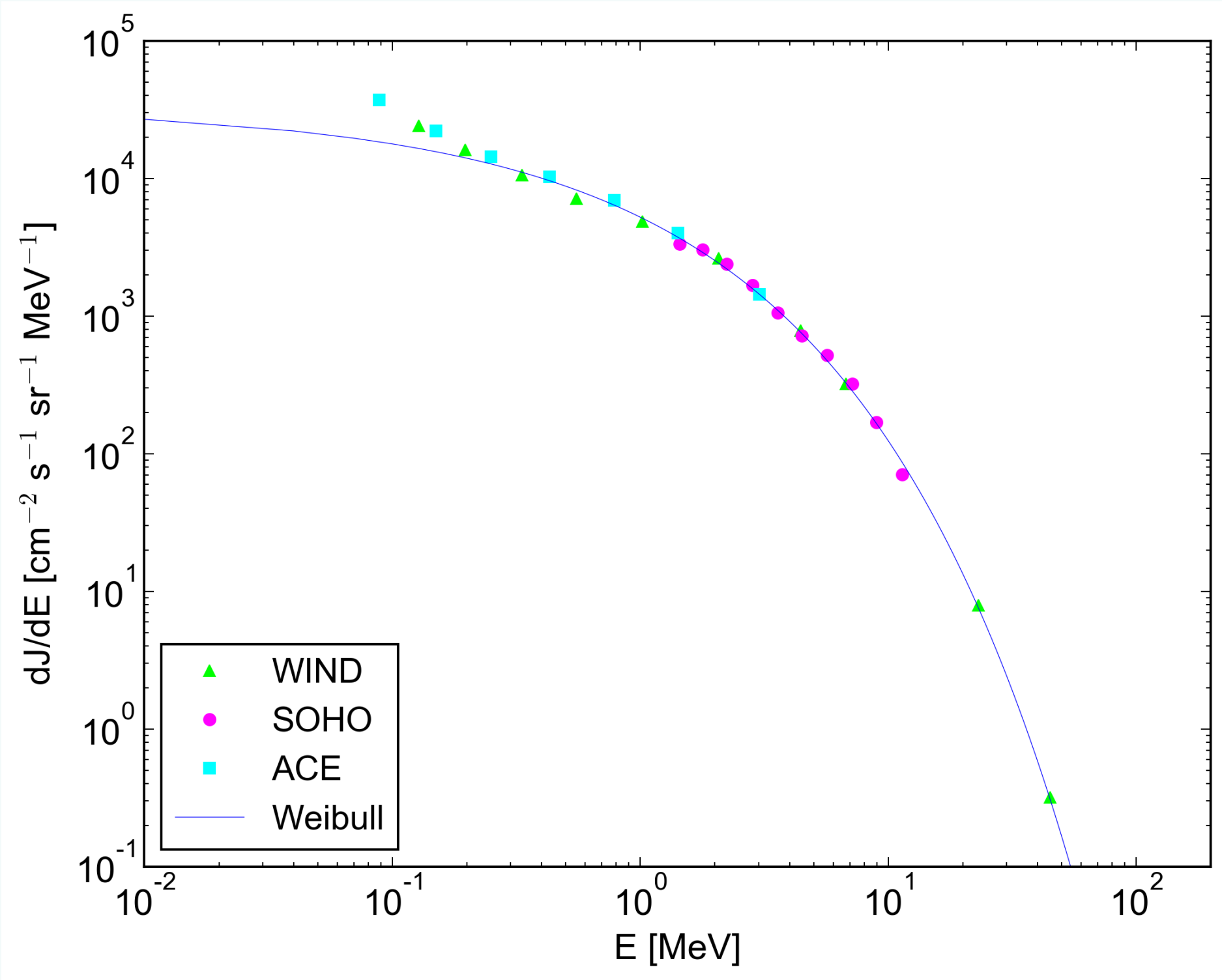


- Magnetic field fluctuations upstream and downstream of the shock were studied using SolO/MAG 0.125 s data (in the RTN frame) and Wind/MFI 0.092 s data (in the GSE frame). Time series of 68 min length were used, avoiding a 5 min interval around the shock. We show here only the SoLO results. Left panel: both the upstream and the downstream PSDs have a clear and wide range with a Kolmogorov-like power law behaviour ($\propto f^{-5/3}$). The downstream PSD is significantly larger (by about one order of magnitude) than the upstream one, as expected due to the enhancement of the fluctuations associated with the shock passage. Center and right panels: flatness of the increments of the field components, upstream and downstream of the shock, as a function of the timescale. In the downstream region, the flatness is significantly larger and increases as τ decreases down to $\tau \approx 1$ s, indicating a higher level of intermittency with respect to the upstream region. More details on this event can be found in Chiappetta et al. (2023).

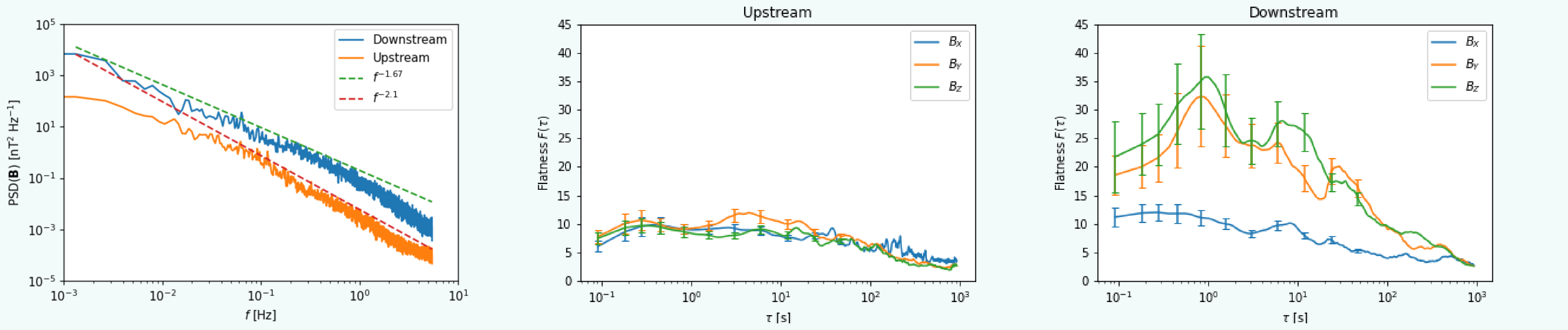


5. The 7 September 2017 ESP Event

- Shock passage at Wind on 7 September at 22:28 UT. The main shock parameters provided by the CfA Wind interplanetary shock database `https://lweb.cfa.harvard.edu/shocks/wi_data/` are: $\theta_{\text{Bn}} \approx 57°$, $M_{\text{ms}} \approx 1.9$, $r \approx 2.5$, $\beta \approx 0.038$.
- To calculate the proton energy spectrum, we used particle flux data from Wind, ACE, and SOHO (all located close to the L1 Lagrangian point). The covered energy range, considering all the three S/C, goes from 40 keV to 72 MeV. Also in this case, a calibration procedure was applied to combine data from different S/C.
- The average differential flux dJ/dE (fig. on the right) was calculated over an interval of three hours around the shock arrival. Using the energy interval [0.4,44.8] MeV, the best fit was obtained with the Webull function (solid line), with a reduced chi-square $\chi^2 = 0.77$. The best-fit parameters are: $\gamma = (0.490 \pm 0.010)$ and $E_\tau = (0.309 \pm 0.030)$ MeV.



- The magnetic field fluctuations were studied using Wind/MFI high resolution (0.092 s) measurements (in the GSE frame). Time series of 50 min length were used, avoiding a 5 min interval around the shock. Left panel: both the PSDs show a clear and wide range with a power law behaviour ($\propto f^{-\alpha}$), with spectral indexes $\alpha \approx 5/3$ downstream, and $\alpha \approx 2$ upstream. As for the other event, the downstream PSD is about an order of magnitude larger than the upstream one. Center and right panels: flatness of the increments of the magnetic field components, calculated upstream and downstream of the shock, as a function of the timescale. In the downstream region the flatness is significantly larger and increases as τ decreases down to $\tau \approx 1$ s for the B_y and B_z components, indicating a higher level of intermittency with respect to the upstream region.



- A comprehensive study of the Space Weather event starting on 6 September 2017, encompassing the whole chain of phenomena occurred from the Sun to the Earth, is presented in the poster SWR02-694 by Laurenza et al.

Conclusions

- Our findings are in agreement with those in Chiappetta et al (2021), with ESP proton spectra at quasi-perpendicular shocks well described by the Weibull function, while the Band function provides the best fit in the case of quasi-parallel shocks.
- In this work, we also found that magnetic field fluctuations around the investigated shocks show an enhancement of the turbulence and intermittency levels in the downstream region.
- These results support the scenario in which two different mechanisms contribute to particle acceleration in different energy ranges, as proposed in some previous works (e.g. Kallenrode 1996, Pallocchia et al. 2017, Chiappetta et al. 2021), diffusive shock acceleration being the dominant mechanism at lower energies, while at higher energies there are indications for the presence of stochastic acceleration by enhanced downstream turbulence.

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