Proton energy spectra of energetic storm particle events and their relation with magnetic turbulence and intermittency nearby interplanetary shocks

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1. Context and motivation

- Energetic storm particle (ESP) events are local increases of energetic charged particle fluxes observed at interplanetary (IP) shocks. Accelerated particles are observed over a wide energy range going from few tens of keV to several tens of MeV, although the intensity enhancements are observed more frequently in low energy ion fluxes.
- ESPs can occur at the shock arrival when a solar energetic particle (SEP) event is in progress or in the absence of SEPs.
- In situ spacecraft (S/C) observations of particle populations associated with ESP and SEP events provide very useful data for the investigation of the physical processes involved in these events, especially the acceleration mechanisms occurring at shocks. The energy spectra obtained from the measured particle fluxes are of particular interest in this context.
- In this work we analyse the kinetic energy spectra of two ESP events associated with SEPs and observed by various S/C. Different functional forms are used to fit the observed spectra and the obtained results are discussed in the context of particle acceleration and in relation to the magnetohydrodynamic (MHD) turbulence in the upstream and downstream regions of the shocks.

2. Fitting functions for the energy spectra and acceleration mechanisms

DSA and Ellison-Ramaty spectrum

- 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.

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

Double power law spectrum

- The double-power-law representation of Band et al. (1993) has been proposed in some works (see e.g. Mewaldt et al 2005) to provide better fits than Ellison-Ramaty function to SEP particle energy spectra.

$$\frac{dJ}{dE} = C\,E^{-\gamma_a}e^{-\left(\frac{E}{E_0}\right)} \quad \text{for } E \le (\gamma_b-\gamma_a)E_0$$
$$\frac{dJ}{dE} = C\,E^{-\gamma_b}\left\{[(\gamma_b-\gamma_a)E_0]^{(\gamma_b-\gamma_a)}\,e^{(\gamma_a-\gamma_b)}\right\} \quad \text{for } E \ge (\gamma_b-\gamma_a)E_0 \qquad (1)$$

- 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

- The Weibull distribution has been 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 would be $\gamma = 0.5$.

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

3. Relation between energy spectra and MHD turbulence around the shocks

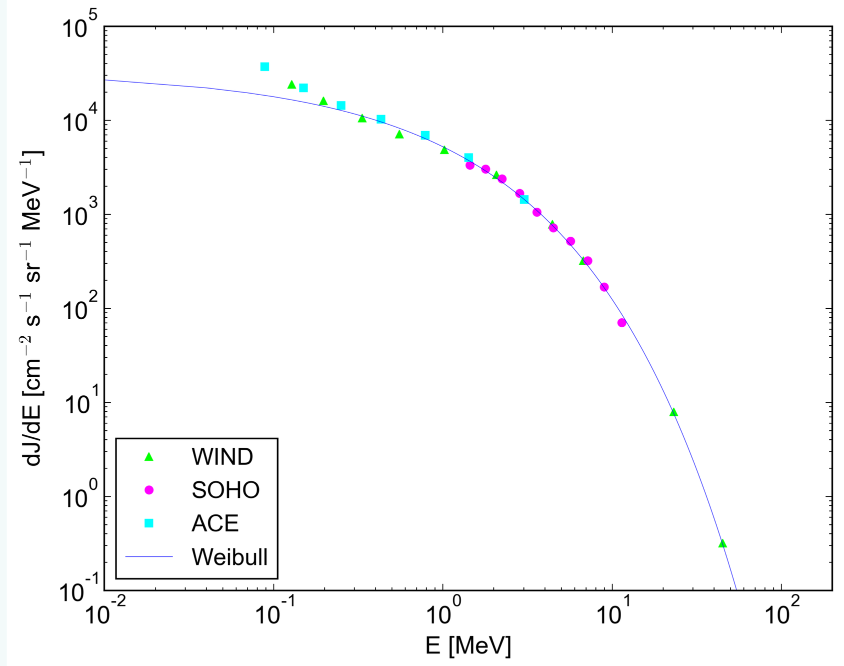
- The characteristics of magnetic turbulence around IP shocks can have a significant impact on the particle acceleration processes, in particular if stochastic acceleration is involved.
- A significant correlation between the high energy ion flux and the turbulence level (quantified by the total power 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 an IP shock can be investigated in more detail by calculating 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)

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

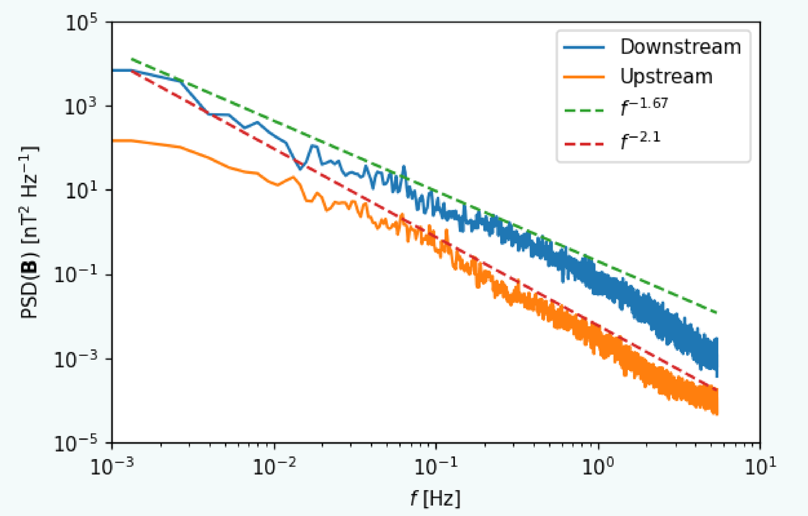
where $S_p^{(i)}(\tau) = \langle|B_i(t+\tau) - B_i(t)|^p\rangle$ are the structure functions of order p of the magnetic field increments, $B_i(t)$ are the magnetic field components, τ the the timescale separation, and $\langle\cdot\rangle$ denotes time average over the considered interval.

4. The 7 September 2017 ESP Event

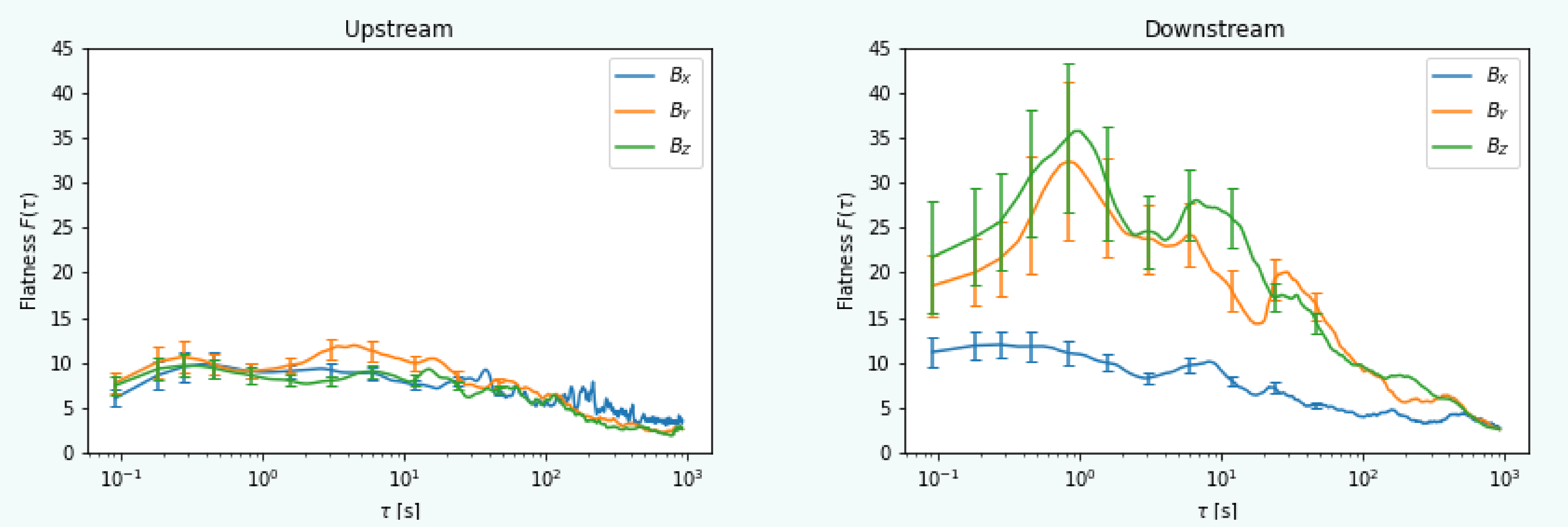
- Shock passage at Wind on 7 September at 22:28 UT. The main shock parameters provided by the CfA Wind interplanetary shock database https://lweb.cfa.harvard.edu/shocks/wi_data/ are: shock-normal angle $\theta_{Bn} \approx 57°$, fast magnetosonic Mach number $M_{ms} \approx 1.9$, compression ratio $r \approx 2.5$, and plasma beta $\beta \approx 0.038$.
- 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. In order to combine the data from different S/C, a calibration procedure was applied between Wind/3DP and SOHO/LED, and between ACE and SOHO/LED.
- The average differential flux dJ/dE (figure 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, among the three functions mentioned in Section 2, is obtained with the Webull function (solid line), with a reduced chi-square $\chi^2 = 0.77$. The best-fit parameters are:
$\gamma = (0.490 \pm 0.010)$
$E_\tau = (0.309 \pm 0.030)$ MeV



- The turbulent magnetic field fluctuations upstream and downstream were studied using Wind/MFI high resolution (0.092 s) measurements (in GSE system). Time series of 50 min length were considered, avoiding a 5 min interval around the shock.
- The downstream PSD is roughly an order of magnitude larger than the upstream one (figure on the right), as expected due to the enhancement of the fluctuations associated with the shock passage. 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.



- The figures below show the flatness of the increments of magnetic field components, calculated upstream and downstream of the shock, as a function of the timescale.

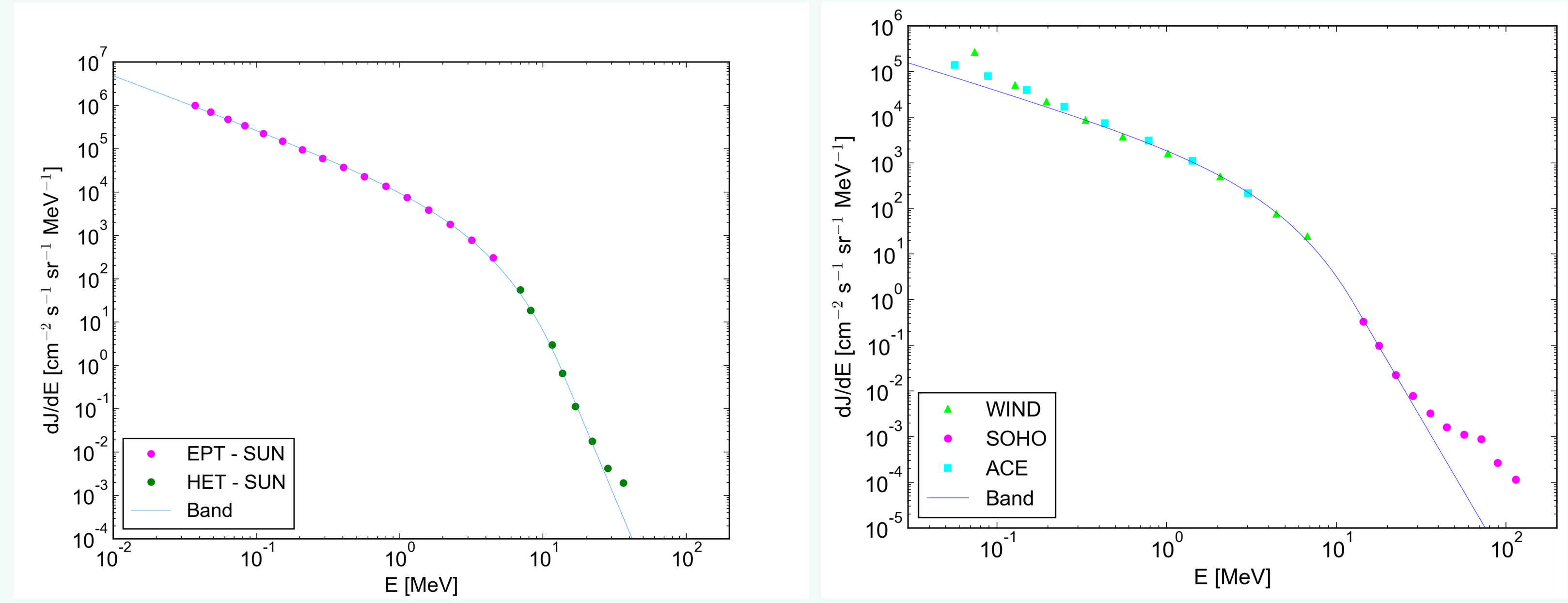


- In the downstream region the flatness is significantly larger and increases as τ decreases down to $\tau \approx 1$ s for the B_y and B_z components, indicating a higher level of intermittency with respect to the upstream region.
- More details on this event in the poster EGU23-4398 by F. Chiappetta et al. (in this session).

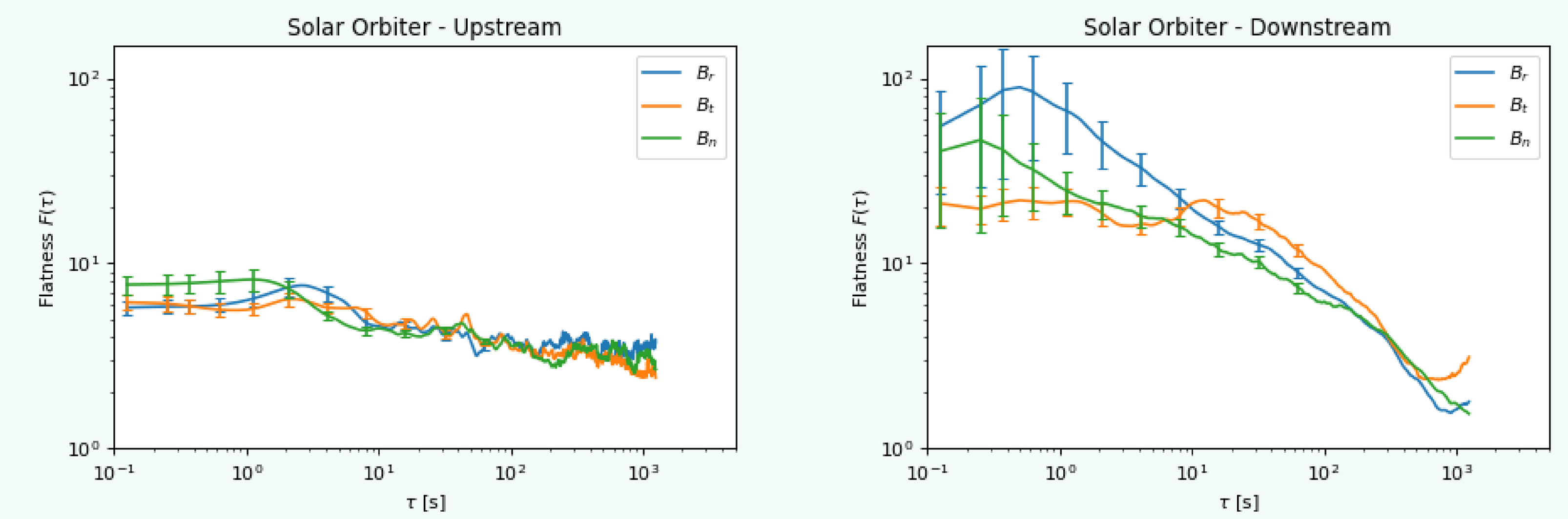
5. The 3 November 2021 ESP Event

- Shock passage at Solar Orbiter (SolO, located at 0.85 AU) at 14:04 UT, and at Wind at 19:35 UT. The shock parameters were calculated by Trotta at al.(2023), and are given below.

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



- Proton energy spectra calculated both for SolO (left panel) and at L1 (right panel, using flux data from Wind, ACE, and SOHO). In this case the best fit is obtained with the Band double power law function. The power law indexes are $\gamma_a \approx 1.2$ at low energies, while at hgh energies $\gamma_b \approx 7.9$ (SolO) and $\gamma_b \approx 6.4$ (L1).



- Magnetic field fluctuations upstrm and downstrm were studied using SolO/MAG 0.125 s data. Time series of 68 min length, avoiding a 5 min interval around the shock. Also for this event, in the downstream region the flatness is significantly larger and increases in a steeper way as τ decreases.

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 the past (e.g. Kallenrode 1996, Pallocchia et al. 2017, Chiappetta et al. 2021), the DSA being the dominant mechanism at low energies, while at higher energies a contribution from SA is present.

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