

LETTER TO THE EDITOR

Energetic particle-mediated interplanetary shocks observed by Solar Orbiter

D. Trotta¹, D. Lario², B. Reville³, S. Raptis⁴, O. Pezzi⁵, H. Hietala⁶, P. Mostafavi⁴, J. Giacalone⁷, R. F. Wimmer-Schweingruber⁸, P. Kuehl⁸, A. Kollhoff⁸, D. Turner⁴, and D. Burgess⁶

¹ European Space Agency (ESA), European Space Astronomy Centre (ESAC), Camino Bajo del Castillo s/n, 28692 Villanueva de la Cañada, Madrid, Spain e-mail: domenico.trotta@esa.int

² Heliospheric Physics Laboratory, Heliophysics Division, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA

³ Max-Planck-Institut für Kernphysik, Heidelberg, Germany

⁴ Johns Hopkins University Applied Physics Laboratory, Laurel, MD, USA

⁵ Istituto per la Scienza e Tecnologia dei Plasmi (ISTP), Consiglio Nazionale delle Ricerche, I-70126 Bari, Italy

⁶ Department of Physics and Astronomy, Queen Mary University of London, Mile End Road, London E1 4NS, UK

⁷ Lunar and Planetary Laboratory, University of Arizona, Tucson, USA

⁸ Institute of Experimental and Applied Physics, Kiel University, Leibnizstrasse 11, D-24118 Kiel, Germany

July 24, 2026

ABSTRACT

Context. In collisionless shocks, energetic particles can carry enough pressure to modify the upstream plasma and the shock structure itself. This represents a regime that is often invoked in theories of cosmic-ray acceleration, but rarely observed in the heliosphere.

Aims. We locate and characterise interplanetary (IP) shocks where energetic particles dynamically dominate the upstream pressure.

Methods. We analysed IP shocks observed by Solar Orbiter within 1 au and computed the energetic particle pressure, P_{EP} , from proton measurements above 10 keV. We compared these results with the upstream thermal P_{Th} and magnetic P_B pressures.

Results. We identified four shocks for which $P_{EP} \geq P_{Th} + P_B$. These events correspond to strong and fast shocks in the high-Mach-number tail of the Solar Orbiter shock population. In several cases, the P_{EP} increase coincides with a decreasing upstream bulk flow speed in the shock frame, with the resulting particle-mediated foreshocks extending up to $\sim 10^5$ ion inertial lengths, d_i . The extent of such an energetic particle-dominated region depends on the shock geometry.

Conclusions. These observations provide evidence that accelerated particles can dynamically modify IP shocks. They highlight the importance of coupling among energetic particles, upstream fluctuations, and shock structure in improving our understanding of particle acceleration at collisionless shocks.

Key words. Shock waves – solar wind – Acceleration of particles

1. Introduction

Energetic particles are ubiquitous in astrophysical environments, yet the mechanisms responsible for their production have been debated since the seminal works of Fermi in the 1950s (Fermi 1949, 1954). Collisionless shocks are sharp transitions from super-sonic/super-Alfvénic to sub-sonic/sub-Alfvénic flows that convert directed upstream kinetic energy into downstream thermal and magnetic energy. Such shocks can channel a significant fraction of this energy into non-thermal particles, placing among the most efficient particle accelerators in astrophysical plasmas. (Balogh & Treumann 2013; Bykov et al. 2019; Giuffrida et al. 2022).

Shocks in the heliosphere provide a unique opportunity to study particle acceleration in situ, unlike shocks in distant astrophysical systems where only indirect diagnostics are possible (Stone & Tsurutani 1985). These observations have provided key tests for particle acceleration theories (e.g., Schwartz et al. 2022; Amano et al. 2020). However, whether insights from heliospheric shocks can be directly extrapolated to astrophysical systems remains debated, since they occupy different regions of parameter space (see, e.g., (Ghavamian et al. 2013)). For example, coronal mass ejection (CME) driven interplanetary (IP)

shocks typically have lower Mach numbers than many other types of astrophysical shocks (e.g., Burgess & Scholer 2015; Pérez-Alanis et al. 2023).

A particularly important, yet poorly explored regime is the energetic particle (or cosmic-ray) dominated regime, in which energetic particle pressure, P_{EP} , exceeds the thermal P_{Th} and magnetic field P_B pressures upstream of the shocks (Drury 1983). Simulations have offered predictions that gradients in P_{EP} could form an upstream precursor that decelerates and modifies the shock, producing compression ratios exceeding the canonical value of four for strong shocks (Reville & Bell 2013; Haggerty & Caprioli 2020). These effects have important implications for energetic particle production and transport (Jones & Ellison 1991).

Observational hints of this regime in the heliosphere have previously been reported near Earth (Lario & Decker 2002) and at the heliospheric termination shock (Florinski et al. 2004). Terasawa et al. (2006) analysed two strong IP shocks observed by Geotail and found signatures consistent with the energetic particle mediated regime, although the energetic particle pressure was not quantified. Subsequently, Lario et al. (2015) identified periods when energetic proton pressure exceeded both magnetic and thermal pressures upstream of IP shocks using

Article number, page 1 of 8

STEREO observations, but the limited energy coverage limited the characterisation of these precursors.

The Solar Orbiter mission (Müller et al. 2020) provides new opportunities to investigate these processes thanks to its advanced energetic particle instrumentation (Rodríguez-Pacheco et al. 2020; Wimmer-Schweingruber et al. 2021). With more than 150 shock events observed since launch until end of 2025 (Trotta et al. 2025), it enables detailed studies of shock-accelerated particles with unprecedented coverage (e.g., Trotta et al. 2023b; Yang et al. 2024).

In this work, we identify and characterise four energetic particle-mediated shocks, providing the first detailed description of energetic particle-mediated shocks using in situ observations. Full details of the instrumentation used and the energetic particle and IP context where these shocks were observed are given in Appendices A and C, respectively.

2. Results and discussion

For each event in the Solar Orbiter shock sample, extending the collection reported in Trotta et al. (2025) to 152 events, we computed P_{EP} 5 hours before and 1 hour after the shock passage using the expression $P_{EP} \equiv (4\pi/3)(2m)^{1/2} \int_{E_1}^{E_2} \sqrt{E} j(E) dE$, where E is the proton kinetic energy, $j(E)$ the proton differential flux, and m the proton mass. We used $E_1 = 10$ keV and $E_2 = 100$ MeV as the lower and upper integration bounds (see Russell et al. 2013; Lario et al. 2015). P_{EP} was then compared to $P_B + P_{Th}$, where $P_B \equiv B^2/2\mu_0$ is the magnetic pressure (B and μ_0 are the magnetic field magnitude and magnetic permeability) and $P_{Th} = 2n_p k_B T_p$ is the thermal pressure (n_p and T_p are the solar wind proton density and temperature, and k_B the Boltzmann constant). Here we assume an electron temperature of $T_e \approx T_p$ (see Shi et al. 2023).

We identified periods where $P_{EP} \geq P_B + P_{Th}$ upstream of the shocks, yielding four events in this regime. An overview of these shocks is shown in Figure 1. For each event, panels a–d display the differential energy flux measured by the sunward apertures of HET/EPT (a,b), pixel-averaged STEP (c), and angle-averaged SWA-PAS (d). The cyan line in panel d marks the peak of the thermal proton distribution, E_{bulk} . The red line in panel c shows $10 \times E_{bulk}$, while the green line indicates the lowest energy E_1 used in the P_{EP} computation. In most cases, E_1 lies above $10 \times E_{bulk}$, confirming that the pressure estimate is dominated by suprathermal and energetic particles. The only exception is S1, where E_1 falls below this threshold; however, repeating the calculation with a higher E_1 does not change the results.

Panel e shows the evolution of the pressure contributions during each event, with P_B , P_{Th} , P_{EP} , and $P_{Th} + P_B$ shown as red, blue, black, and green lines, respectively. The magenta shaded regions mark intervals where $P_{EP} \geq P_B + P_{Th}$. In panel e, we include the ram pressure along the shock normal, P_{ram} , computed in the normal incidence shock frame (NIF; see Appendix B). In several cases, decreases in P_{ram} coincide with the largest increases in P_{EP} .

Panel f shows the plasma velocity along the shock normal in the shock rest frame (blue), with the horizontal grey line indicating its upstream average value. In three of the four events, the upstream velocity increases prior to the shock, consistent with the action of an energetic particle pressure precursor; this signature is weaker for S1. Panels g and h show n_p and T_p (g), along with the magnetic field magnitude and components (h).

Figure 1 shows that the periods with $P_{EP} \geq P_{Th} + P_B$ occur under a range of upstream conditions, from the short-lived event

of S2 in a relatively quiet solar wind to the prolonged case of S4 embedded in a highly structured upstream medium. The properties of the four shocks are summarised in Table 1. Full details on the parameters and their determination are provided in Appendix B. Together with the typical shock parameters, we report τ_{EP} , the duration for which $P_{EP} \geq P_{Th} + P_B$ upstream of the shock, and L_{EP} , obtained by converting this duration into a spatial scale using the shock speed and expressing it in units of the ion inertial length d_i . Finally, S1,2,3, and 4 occur at heliocentric distances of .92, .68, .72, and .92 AU, respectively.

All events correspond to fast and strong shocks, with shock speeds between ~ 600 and 1000 km s^{-1} and Alfvénic and fast magnetosonic Mach numbers in the ranges $M_A \sim 6\text{--}8$ and $M_{fms} \sim 4\text{--}7$. The shocks span a range of geometries, from quasi-parallel to quasi-perpendicular ($\theta_{Bn} = 35^\circ\text{--}72^\circ$), indicating that the energetic particle-mediated regime is not restricted to a specific shock orientation. The duration of the energetic particle precursor τ_{EP} varies widely, from only a few minutes for S2 to more than 100 minutes for S3 and 4, corresponding to precursor scales of $\sim 10^3 - 10^5 d_i$. The peak value of $P_{EP}/(P_B + P_{Th})$ is of 2.5, 2.3, 3 and 3.1 for S1 to 4, respectively.

These results indicate that extended energetic-particle dominated precursors are generated upstream of strong fast shocks. From this point of view, our results show that energetic particle-mediated shocks require parameters at the extreme of the IP-shock parameter distributions (Kilpua et al. 2015; Pérez-Alanis et al. 2023). This finding is consistent with previous observations (Russell et al. 2013; Terasawa et al. 2006; Lario et al. 2015) and with theoretical expectations that stronger shocks are more efficient at accelerating particles; therefore, they have the capacity to reach the energetic particle mediated regime more readily (e.g., Bell 2013).

To further quantify the unusual nature of these shocks, we compared their fast magnetosonic Mach numbers with the full Solar Orbiter shock sample. The violin plot in Figure 2a) shows the distribution of M_{fms} for all shocks, with the four energetic particle-mediated events highlighted. All four lie in the high-Mach-number tail of the distribution, demonstrating that the energetic particle-mediated regime occurs only for the strongest IP shocks, with an occurrence of about 3% over the 152 events analyzed. Similar results are obtained when using M_A or the shock speed.

To investigate which shock properties control the development of the energetic particle precursor, we explored correlations between the precursor length, L_{EP} , and the main shock parameters, including shock speed, Mach numbers, and shock geometry. Among the quantities examined, the shock normal angle, θ_{Bn} , shows the clearest relationship with the precursor extent. Figure 2b) illustrates this trend by showing the precursor length, L_{EP} as a function of θ_{Bn} . This behavior is consistent with the role of shock geometry in controlling particle transport upstream of the shock. Quasi-parallel shocks (smaller θ_{Bn}) allow particles to escape farther upstream, producing extended precursors, whereas quasi-perpendicular shocks tend to confine particles closer to the shock (Lario et al. 2019). The observed variation of L_{EP} with θ_{Bn} is therefore consistent with theoretical expectations for energetic particle transport at collisionless shocks (Reville & Bell 2013).

We also note that three of the four shocks (all except the quasi-perpendicular shock 2) occur after large solar energetic particle (SEP) events (Appendix C), providing a substantial ‘seed’ population of energetic particles upstream of the shock (see Kahler et al. 2000; Wijzen et al. 2023). In addition, the two most quasi-parallel shocks in our sample exhibit signatures of a wave foreshock upstream of the shock (see Appendix D).

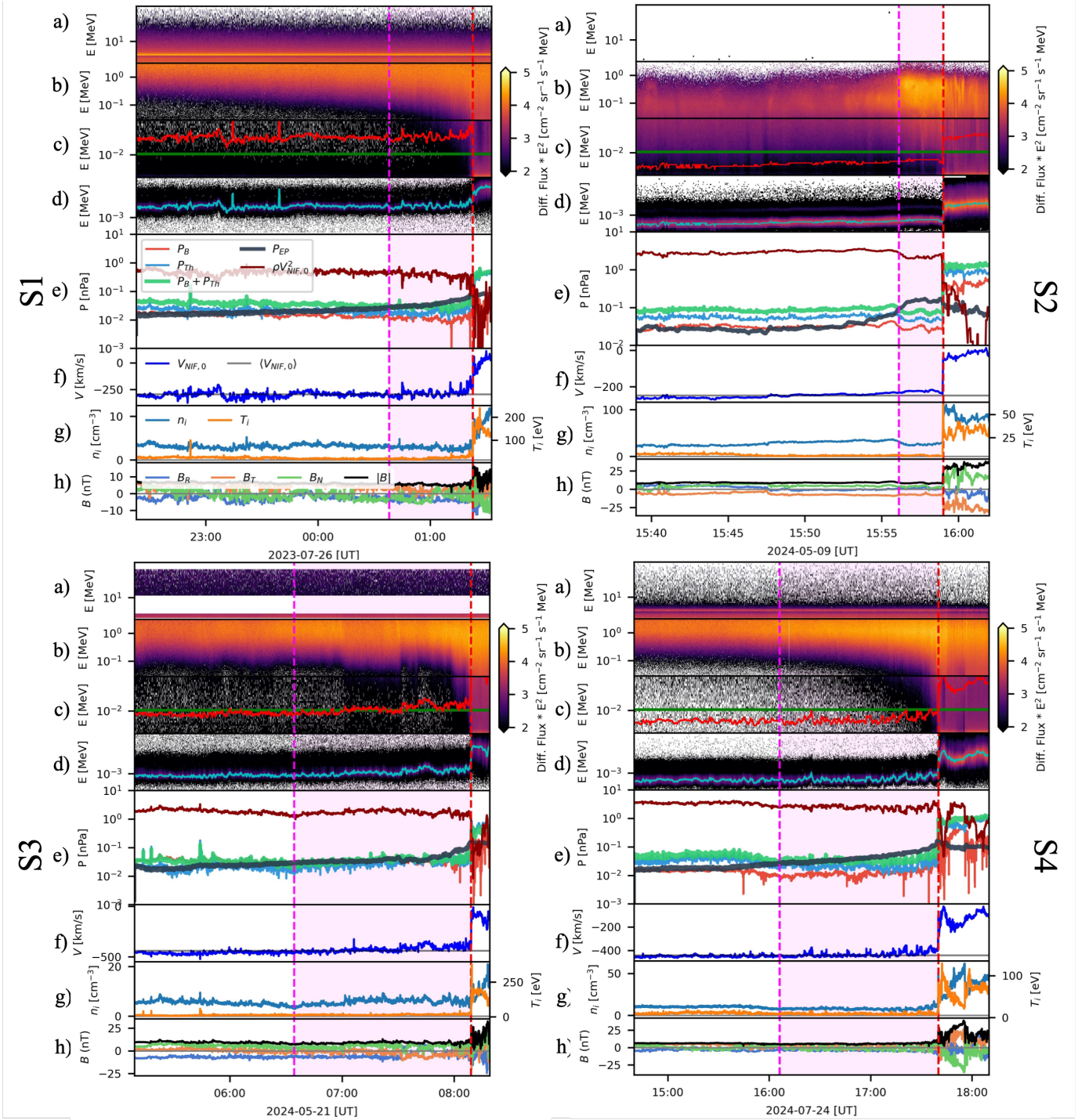


Fig. 1. Overview of the four energetic particle-mediated shocks. a–d: Differential energy flux measured by the sunward apertures of HET/EPT (a,b) pixel-averaged STEP (c), and angle-averaged SWA-PAS (d). The cyan line marks the peak of the thermal proton distribution, E_{bulk} , the red line shows $10E_{bulk}$, and the green line indicates the lower integration limit, E_1 , used in the energetic particle pressure calculation. e: Evolution of the pressure contributions: magnetic pressure, P_B (red), thermal pressure, P_{Th} (blue), energetic particle pressure, P_{EP} (black), and $P_{Th} + P_{EP}$ (green) and the ram pressure, $\rho V_{NIF,0}^2$, along the shock normal in the shock rest frame (dark red). Magenta shading marks intervals where $P_{EP} \geq P_B + P_{Th}$. f: Plasma velocity along the shock normal in the shock rest frame (blue), with the grey line indicating the upstream average. g–h: Ion density and temperature, and the magnetic field magnitude and components, respectively.

Table 1. Energetic particle-mediated shocks and their parameters. Details of their computation are given in Appendix B.

Name	Shock time [UTC]	r_G	r_B	Normal (RTN)	v_{sh} [km/s]	M_A	M_{fms}	θ_{Bn} [°]	τ_{EP} [min]	L_{EP} [d_i]
S1	2023-07-26 01:22:46	2.1	2.1	[0.88, -0.18, 0.44]	997	6.3	4.3	48	44	19500
S2	2024-05-09 15:58:59	3.5	3.7	[0.97, -0.17, 0.13]	637	7.7	5.8	72	3	2500
S3	2024-05-21 08:09:05	2.0	2.2	[0.91, 0.21, -0.36]	990	6.5	5.5	37	95	59000
S4	2024-07-24 17:40:01	2.1	2.2	[0.98, -0.04, 0.20]	820	8.1	6.9	40	93	56500

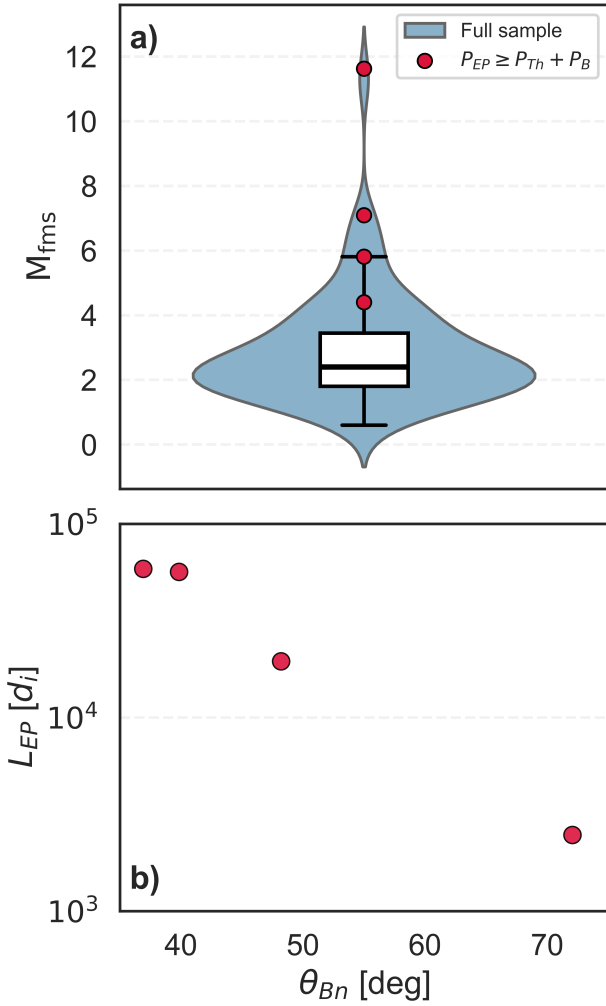


Fig. 2. a: Distribution of the fast magnetosonic Mach number M_{fms} for the Solar Orbiter shocks. The violin plot shows the full distribution, with the box indicating the interquartile range and median. The four shocks identified in this work with $P_{EP} \geq P_B + P_{Th}$ are highlighted in red. b: Upstream precursor length L_{EP} as a function of the shock normal angle, θ_{Bn} , for the four energetic particle-mediated shocks.

3. Conclusions

We identified four IP shocks in the Solar Orbiter sample for which the upstream energetic particle pressure was shown to exceed the combined thermal and magnetic pressures, placing them in the energetic particle-mediated regime. These events are associated with strong and fast shocks that lie in the high-Mach-number tail of the Solar Orbiter shock population. In several cases, the increase in the energetic particle pressure coincides with a decrease in ram pressure and a decrease of upstream bulk flow speed in the shock frame. The spatial extent of these energetic particle-mediated foreshocks reached $\sim 10^3$ – $10^5 d_i$ and exhibited a dependence on shock geometry, with more quasi-parallel shocks producing more extended energetic particle-dominated foreshocks. We also note that three of the four shocks followed SEP events, suggesting that a substantial seed population could play a role in the development of this regime. The highly dynamic energetic-particle signatures of these four events provide a unique opportunity to probe particle–shock–ambient-plasma coupling (Wimmer-Schweingruber et al. 2026).

These observations provide direct evidence that accelerated particles have the capacity to dynamically modify the upstream medium of IP shocks, linking energetic particle pressure, upstream fluctuations, and shock structure. Upstream particle-driven modifications are also observed at Earth’s bow shock, although they are typically associated with lower-energy particles and occur in a stationary shock environment (Johlander et al. 2021; Lalti et al. 2022). Recent comparisons between planetary and IP compressive foreshocks further highlight these connections (Raptis et al. 2026). A direct comparison with the energetic particle-mediated IP shocks identified here will be the subject of a future work.

References

- Amano, T., Katou, T., Kitamura, N., et al. 2020, *Phys. Rev. Lett.*, 124, 065101
 Balogh, A. & Treumann, R. A. 2013, *Physics of Collisionless Shocks: Space Plasma Shock Waves*, Vol. 12
 Bell, A. 2013, *Astroparticle Physics*, 43, 56, seeing the High-Energy Universe with the Cherenkov Telescope Array - The Science Explored with the CTA
 Bruno, R. & Carbone, V. 2013, *Living Reviews in Solar Physics*, 10, 2
 Burgess, D. & Scholer, M. 2015, *Collisionless Shocks in Space Plasmas* (Cambridge University Press)
 Bykov, A. M., Vazza, F., Kropotina, J. A., Levenfish, K. P., & Paerels, F. B. S. 2019, *Space Sci. Rev.*, 215, 14
 Dimmock, A., Gedalin, M., Lalti, A., et al. 2023, *A&A*, 679, A106
 Drury, L. O. 1983, *Reports on Progress in Physics*, 46, 973
 Fermi, E. 1949, *Physical Review*, 75, 1169
 Fermi, E. 1954, *ApJ*, 119, 1
 Florinski, V., Zank, G. P., Jokipii, J. R., Stone, E. C., & Cummings, A. C. 2004, *ApJ*, 610, 1169
 Fränz, M. & Harper, D. 2002, *Planet. Space Sci.*, 50, 217
 Ghavamian, P., Schwartz, S. J., Mitchell, J., Masters, A., & Laming, J. M. 2013, *Space Sci. Rev.*, 178, 633
 Giacalone, J., Trotta, D., Mitchell, D. G., et al. 2025, *ApJ*, 996, 87
 Giuffrida, R., Miceli, M., Caprioli, D., et al. 2022, *Nature Communications*, 13, 5098
 Haggerty, C. C. & Caprioli, D. 2020, *ApJ*, 905, 1
 Horbury, T. S., O’Brien, H., Carrasco Blazquez, I., et al. 2020, *A&A*, 642, A9
 Johlander, A., Battarbee, M., Vaivads, A., et al. 2021, *ApJ*, 914, 82
 Jones, F. C. & Ellison, D. C. 1991, *Space Sci. Rev.*, 58, 259
 Kahler, S. W., Reames, D. V., & Burkepile, J. T. 2000, in *Astronomical Society of the Pacific Conference Series*, Vol. 206, *High Energy Solar Physics Workshop - Anticipating Hest!*, ed. R. Ramaty & N. Mandzhavidze, 468
 Kilpua, E. K., Lumme, E., Andreeva, K., Isavnin, A., & Koskinen, H. E. 2015, *J. Geophys. Res.*, 120, 4112
 Koval, A. & Szabo, A. 2008, *J. Geophys. Res.*, 113
 Lalti, A., Khotyaintsev, Y. V., Dimmock, A. P., et al. 2022, *J. Geophys. Res.*, 127, e2022JA030454, e2022JA030454 2022JA030454
 Lario, D., Berger, L., Decker, R. B., et al. 2019, *AJ*, 158, 12
 Lario, D. & Decker, R. B. 2002, *Geophys. Res. Lett.*, 29, 31
 Lario, D., Decker, R. B., Roelof, E. C., & Viñas, A.-F. 2015, *ApJ*, 813, 85
 Lario, D., Hu, J., Balmaceda, L. A., et al. 2026, *ApJ*, 998, 260
 Maksimovic, M., Bale, S. D., Chust, T., et al. 2020, *A&A*, 642, A12
 Möstl, C., Davies, E. E., Weiler, E., et al. 2026, *ApJ*, 1001, 70
 Müller, D., St. Cyr, O. C., Zouganelis, I., et al. 2020, *A&A*, 642, A1
 Owen, C. J., Bruno, R., Livi, S., et al. 2020, *A&A*, 642
 Paschmann, G. & Schwartz, S. J. 2000, *ESA Special Publication*, Vol. 449, *ISSI Book on Analysis Methods for Multi-Spacecraft Data* (ESA), 99
 Pérez-Alanis, C. A., Janvier, M., Nieves-Chinchilla, T., et al. 2023, *Sol. Phys.*, 298, 60
 Raptis, S., Trotta, D., Turner, D. L., et al. 2026, *ApJ*, 1000, L55
 Reville, B. & Bell, A. R. 2013, *MNRAS*, 430, 2873
 Rodríguez-Pacheco, J., Wimmer-Schweingruber, R. F., Mason, G. M., et al. 2020, *A&A*, 642, A7
 Russell, C. T., Mewaldt, R. A., Luhmann, J. G., et al. 2013, *ApJ*, 770, 38
 Schwartz, S. J., Goodrich, K. A., Wilson III, L. B., et al. 2022, *J. Geophys. Res.*, 127
 Shi, C., Velli, M., Lionello, R., et al. 2023, *ApJ*, 944, 82
 Stone, R. G. & Tsurutani, B. T. 1985, *Geophysical Monograph Series*, 34
 Terasawa, T., Oka, M., Nakata, K., et al. 2006, *Advances in Space Research*, 37, 1408
 Trotta, D., Dimmock, A., Hietala, H., et al. 2025, *ApJS*, 277, 2
 Trotta, D., Hietala, H., Horbury, T., et al. 2023a, *MNRAS*, 520, 437
 Trotta, D., Horbury, T. S., Lario, D., et al. 2023b, *ApJ*, 957, L13
 Trotta, D., Vuorinen, L., Hietala, H., et al. 2022, *Frontiers in Astronomy and Space Sciences*, 9
 Welch, P. 1967, *IEEE Transactions on Audio and Electroacoustics*, 15, 70
 Wijzen, N., Lario, D., Sánchez-Cano, B., et al. 2023, *ApJ*, 950, 172
 Wimmer-Schweingruber, R. F., Janitzek, N. P., Pacheco, D., et al. 2021, *A&A*, 656, A22
 Wimmer-Schweingruber, R. F., Trotta, D., Kieokaew, R., et al. 2026, *A&A*, 705, A98
 Yang, L., Heidrich-Meisner, V., Wang, W., et al. 2024, *A&A*, 686, A132

Appendix A: Data products

We used the full in situ Solar Orbiter payload. Magnetic field data are obtained from the flux-gate magnetometer (MAG; Horbury et al. 2020), operating at 64 vectors s^{-1} in burst mode. Ion energy fluxes and plasma moments are provided by the Proton Alpha Sensor (PAS) of the Solar Wind Analyzer (SWA) suite (Owen et al. 2020) at a cadence of 4 s. For S1, the electron density is also estimated from the spacecraft potential measured by the Radio and Plasma Waves instrument (RPW; Maksimovic et al. 2020), available at a temporal resolution of 0.01 s. We used this product to check the consistency with the PAS-measured density.

Energetic particles were measured by the Energetic Particle Detector (EPD) suite (Rodríguez-Pacheco et al. 2020). We used the SupraThermal Electrons and Protons (STEP) sensor, which measures ions from a few keV up to ~ 80 keV using 15 sunward-pointing pixels. We used higher-energy ions measured by the sunward apertures of the Electron Proton Telescope (EPT), covering energies from 25 keV to 6.4 MeV, and of the High Energy Telescope (HET), covering energies from 6.8 to above 100 MeV nuc^{-1} depending on the ion species; in this work, we only used their proton measurements. All energetic particle datasets were taken at 5 s resolution. The fields of view of STEP, EPT, and HET partially overlap and have angular widths of approximately 30° .

Appendix B: Shock parameters and frames

Appendix B.1: Shock parameters and their estimation

The upstream plasma conditions play a key role in determining the properties of collisionless shocks (Burgess & Scholer 2015). One of the most important geometric parameters is the angle between the shock normal and the upstream magnetic field, θ_{Bn} . When θ_{Bn} approaches 90° , the magnetic field lies nearly tangent to the shock surface and the shock is classified as quasi-perpendicular. Smaller values of θ_{Bn} correspond to quasi-parallel configurations.

Shock dynamics are also characterised by several key dimensionless parameters. In particular, the Alfvénic and fast magnetosonic Mach numbers are defined as $M_A = v_{sh}/v_A$ and $M_{fms} = v_{sh}/c_{fms}$, where v_{sh} is the shock speed in the upstream frame and v_A and c_{fms} are the upstream Alfvén and fast magnetosonic speeds. Additional quantities used to describe the shock include the upstream plasma beta ($\beta = v_{th}^2/v_A^2$) and the compression ratios of density and magnetic field across the shock transition, $r_G = n_d/n_u$ and $r_B = B_d/B_u$, where the subscripts u and d denote upstream and downstream quantities.

Determining these parameters from single-spacecraft observations is inherently challenging because shocks are three-dimensional and often highly variable structures (e.g. Koval & Szabo 2008). In this work, shock normals are estimated using the mixed-mode 3 (MX3) method, while the shock speed is derived along the normal direction by enforcing mass flux conservation in the spacecraft frame. A detailed description of this technique can be found in Paschmann & Schwartz (2000). Once the shock normal and speed are obtained, additional quantities such as Mach numbers and compression ratios are derived from the upstream and downstream plasma measurements.

An important source of uncertainty in this procedure arises from the choice of upstream and downstream averaging intervals. Because the plasma environment around shocks is often highly structured, the inferred shock parameters can depend on

the selected time windows (Paschmann & Schwartz 2000). To account for this effect, we systematically vary the averaging intervals and compute distributions of parameter estimates following the approach described in Trotta et al. (2022). All parameters reported in this work are obtained using this method, implemented in the publicly available SerPyShock package¹ developed within the SERPENTINE project. In this work, we varied the averaging windows ranging from 30 s to 1 min, to capture the local regime of the shock front.

Appendix B.2: Shock frames

In the Solar Orbiter datasets, all vector quantities are expressed in spacecraft-centered Radial–Tangential–Normal (RTN) coordinates (Fränz & Harper 2002), where R points radially away from the Sun, T is approximately along the orbital direction, and N completes the right-handed system and is roughly northward with respect to the solar rotation axis.

For the analysis shown in panels f) of Figure 1, plasma velocities are also expressed in the shock normal incidence frame (NIF) (Burgess & Scholer 2015). In this coordinate system, the first axis is aligned with the shock normal $\hat{n}_{shock}$, while the two perpendicular directions are defined relative to the upstream magnetic field. Specifically, we construct $\hat{t}_2 = (\hat{n}_{shock} \times \mathbf{B}_u)/|\hat{n}_{shock} \times \mathbf{B}_u|$ and $\hat{t}_1 = \hat{t}_2 \times \hat{n}_{shock}$, where $\mathbf{B}_u$ is the average upstream magnetic field and $\hat{n}_{shock}$ is obtained from the MX3 method (see Section B.1). This orthogonal basis defines the NIF coordinate system. In this frame, the upstream plasma velocity projected along the shock normal, $V_{NIF,0}$, is negative, indicating flow directed toward the shock. For further details, see Dimmock et al. (2023).

Appendix C: Large scale SEP context

We investigated the large-scale context of the energetic particle-dominated shock events. Figure C.1 shows an overview of the in-situ Solar Orbiter observations for a period of two days prior and after the passage of the S1-4 (shown counter-clockwise). Panel a displays energetic particle intensities at selected energy channels of STEP and the sunward-looking apertures of EPT and HET. Panels b-d display the magnetic field magnitude and angular directions in RTN coordinates and Panels e-g show the solar wind proton bulk speed, n_p and T_p . We note that during the periods of shocks 2 and 3, the onboard EPD software used an outdated temperature configuration that affected the onboard HET calibration tables, making necessary a data recalibration to obtain particle intensities into physical units (Lario et al. 2026). The different energies during these two periods (indicated in Figure C.1) have been used in computation of P_{EP} .

For S1, 3, and 4, the shock arrival is preceded by a strong injection of SEPs occurring at the time indicated by the green arrows. As a result, the upstream regions of these shocks contain a substantial seed population of pre-energised particles. For shock 2, with a less energetic population of particles prior to the shock arrival, a clear association with a solar eruption origin of both this injection of energetic particles and of the IP shock could not be unambiguously made (Lario et al. 2026). Interestingly, this event also exhibits the shortest energetic particle-mediated precursor, although it displays the most pronounced intensity enhancement at the shock itself.

These observations suggest that the presence of pre-energised particles may contribute to the development of ex-

¹ <https://github.com/trottadom/SerPyShock>

tended energetic particle-mediated precursors. However, the relationship between seed populations and shock-driven acceleration remains uncertain and is an active topic of investigation (Giacalone et al. 2025).

Appendix D: Wave foreshocks

To investigate the presence of upstream wave activity associated with the energetic particle-mediated shocks, we analysed magnetic field fluctuations measured by the Solar Orbiter magnetometer (MAG). For each event, we examined a several hour interval surrounding the shock crossing, extending three hours upstream and 1.5 hours downstream of the shock.

Magnetic field power spectral densities (PSDs) were computed in successive sliding windows upstream of the shock. Each spectrum was obtained using a 20-minute interval with a 10-minute step, applying a Welch method to the magnetic field magnitude time series (Welch 1967). The resulting spectra were then ordered according to their temporal distance from the shock and displayed together to illustrate the evolution of magnetic fluctuations as the spacecraft approached the shock.

Figure D.1 shows the PSDs for the four events. The color scale indicates the time relative to the shock arrival, allowing the progressive development of upstream fluctuations to be visualised. For reference, a $f^{-5/3}$ slope is shown, corresponding to the typical inertial-range scaling of solar wind turbulence (Bruno & Carbone 2013). Deviations from this background spectrum and enhanced power at low frequencies indicate the presence of foreshock wave activity generated by particles streaming upstream of the shock.

From Fig. D.1, the clearest foreshock signatures can be observed for shocks 3 and 4. These events also exhibit the longest energetic particle-mediated precursors and correspond to the lowest values of θ_{Bn} in our sample. This behaviour is consistent with the expected dependence of foreshock wave activity on shock geometry, as quasi-parallel shocks allow particles to propagate further upstream and generate enhanced magnetic fluctuations. Albeit comparing IP foreshocks to the much better understood Earth's foreshock is an area of active research (Trotta et al. 2023a; Raptis et al. 2026), we conclude that the foreshock signatures shown in Figure D.1 are not unique to the energetic particle-mediated regime, but are a natural consequence of particle reflection and streaming upstream of quasi-parallel shocks.

Appendix E: Acknowledgements

Acknowledgements. DT acknowledges support through the European Space Agency (ESA) Research Fellowship in Space Science. We acknowledge support from ESA through the Science Faculty - Funding reference ESA-SCI-ELE-170. OP acknowledges support from ESA through the Archival Research Visitor Programme. P. M. acknowledges the partial support by NASA HGIO grant 80NSSC23K0419 and the NSF SHINE grant 2401162. OP is supported by the FIS2 Starting Grant FIS-2023-00246 “PhAse-sPAce cOMplexity in turbulent nearly-reversible plasmas (PAPAO)” (CUP B53C24009610001) funded by the Italian Ministry of University and Research. Work at Kiel university is supported by DLR grant 50 OC 2002.

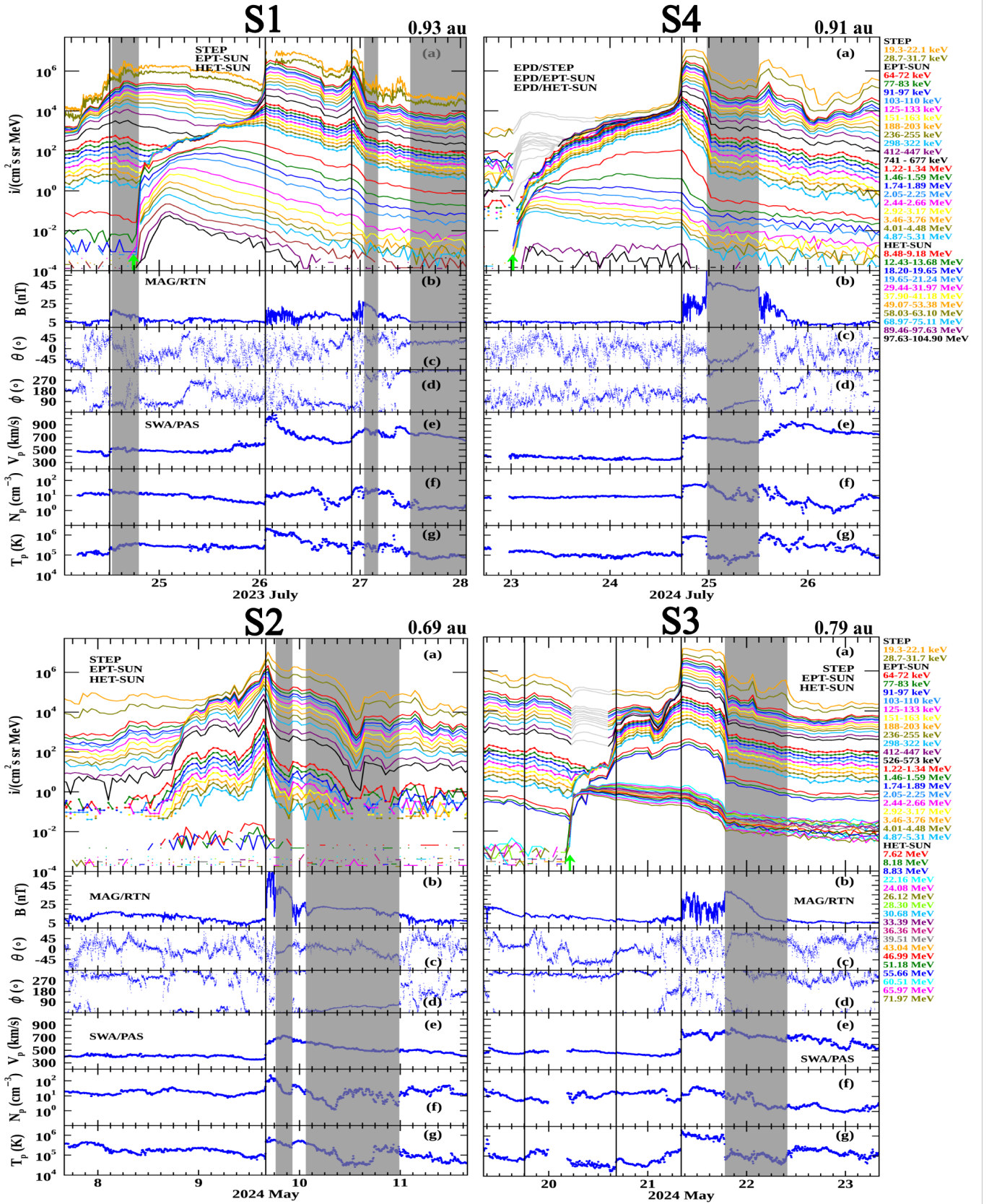


Fig. C.1. Large-scale context for the shocks 1-4 (shown counterclockwise) as seen from Solar Orbiter. Each panel is center at the passage of the shock and covers two days prior and after the shock passage. Each subpanel shows (a) hourly averages of energetic particle intensities measured at selected energy channels of STEP and the sun apertures of EPT and HET; one-minute averages of magnetic field (b) magnitude, and (c-d) angular direction in RTN coordinates; 10-minute averages of the solar wind proton (e) bulk speed, (f) density, and (g) temperature. The vertical solid lines indicate the passage of IP shocks and the shaded gray columns the passage of ICMEs as identified in helioforecast.space/icmecat (Möstl et al. 2026).

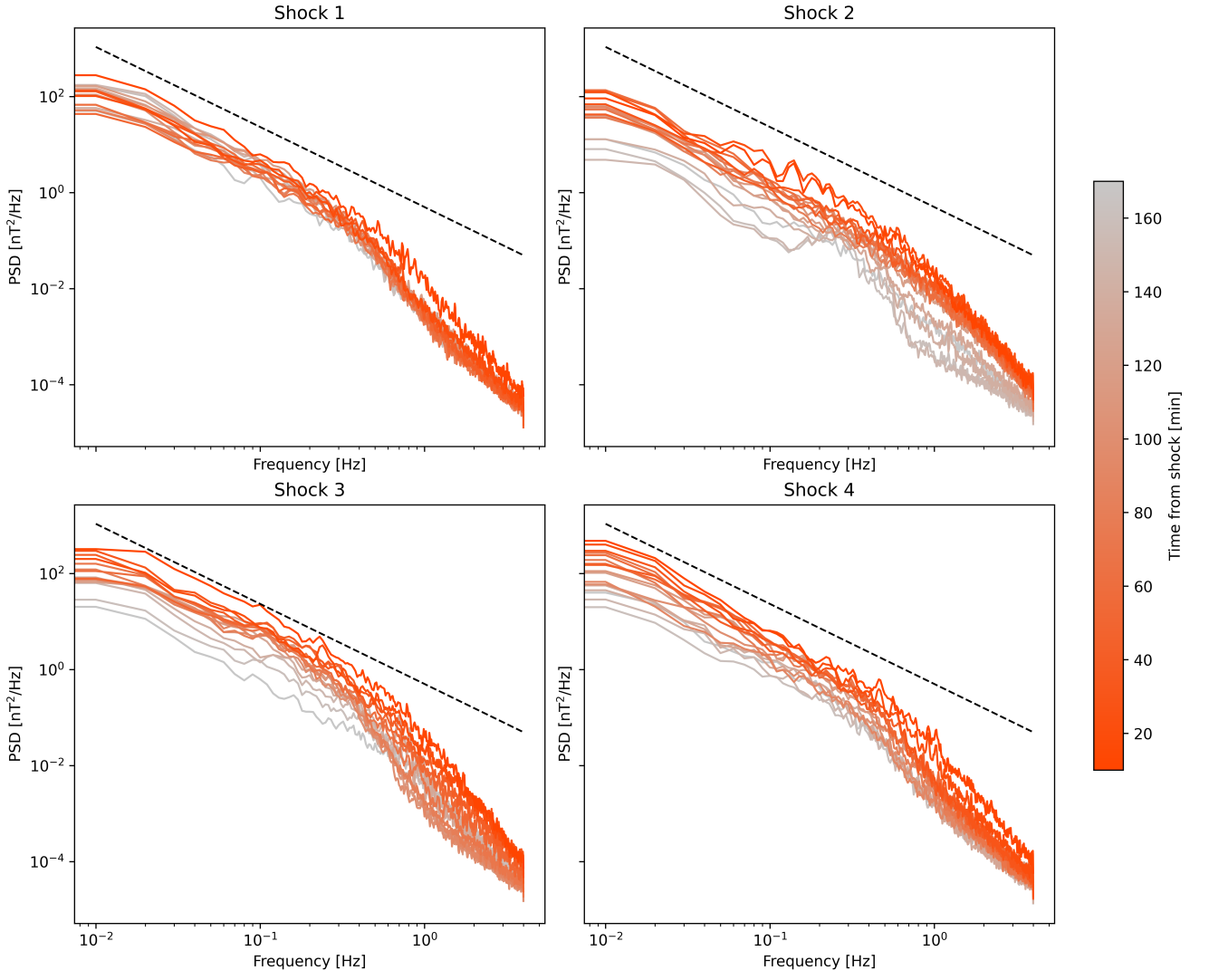


Fig. D.1. Magnetic field power spectral densities upstream of the four shock events. For each shock (panels 1–4), spectra are computed using sliding 20-minute windows shifted by 10 minutes and ordered by their time relative to the shock crossing, with darker colors corresponding to spectra closer to the shock. The dashed line shows a reference $f^{-5/3}$ slope.