Bi-directional streaming of particles accelerated at the STEREO-A shock on 9th March 2008

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ABSTRACT

We present an interpretation of anisotropy and intensity of supra-thermal ions near a fast quasi-perpendicular reverse shock measured by Solar Terrestrial Relations Observatory Ahead (STEREO-A) on 2008 March 9th. The measured intensity profiles of the supra-thermal particles exhibit an enhancement, or "spike", at the time of the shock arrival and pitch-angle anisotropies before the shock arrival are bi-modal, jointly suggesting trapping of near-scatter-free ions along magnetic field lines that intersect the shock at two locations. We run test-particle simulations with pre-existing upstream magnetostatic fluctuations advected across the shock. The measured bi-modal upstream anisotropy, the nearly field-aligned anisotropies up to \(\sim 15\) minutes upstream of the shock, as well as the "pancake-like" anisotropies up to \(\sim 10\) minutes downstream of the shock are well reproduced by the simulations. These results, in agreement with earlier works, suggest a dominant role of the large-scale structure (100s of supra-thermal proton gyroradii) of the magnetic field in forging the early-on particle acceleration at shocks.

Key words: acceleration of particles – shock waves – turbulence

1 INTRODUCTION

The association of energetic charged particles with interplanetary (hereafter IP) shocks is an observational and theoretical pillar of space physics and astrophysics (e.g., Treumann 2009; Burgess et al. 2012). Diffusive shock acceleration theory (Axford et al. 1977; Bell 1978; Blandford & Ostriker 1978; Krymskii 1977; Jokipii 1982) is generally applicable only to particles at sufficiently high energy that the pitch-angle distribution (hereafter PAD) is nearly isotropic. Recent research has been vastly focusing on the origin of these so-called "seed-particles", that include 1) Solar Wind (hereafter SW) particles accelerated directly from the thermal pool during solar energetic particle events, likely at shocks (Neergaard Parker & Zank 2012; Neergaard Parker et al. 2014; Giacalone 2017); 2) pre-existing quiescent population of supra-thermal particles, suggested early-on, e.g., by a He/H intensity ratio of \(\sim 30\) keV ions upstream of the Earth bow shock correlated to the He/H intensity ratio in the SW in contrast with the intensity ratio in the field-aligned beams (Ipavich et al. 1984, 1988, ISEE 1), or by the intensity of \(\sim 35\) keV ions upstream of IP shocks detectable only in a small fraction of the analysed sample (3 events out of 17) by Gosling et al. (1984) in ISEE 1 and ISEE 3 or other works (Desai et al. 2006a, b; Mewaldt et al. 2007; Kahler et al. 2009; Mason et al. 2012). However, a mixture of both populations has not been observationally ruled out (Desai & Giacalone 2016).

Multiple spacecraft (hereafter s/c) measurements at 1 AU (ACE, Wind, Lario et al. 2019) have shown in the supra-thermal energy range (\(\sim 10\) keV ions in the s/c frame) a below-background spectrum upstream of some IP shocks of various magnetic obliquity, i.e., both close to parallel and to perpendicular; only very close (\(\lesssim 5\) minutes) to the shock arrival a supra-thermal component emerges above the \(\sim 1\) count/sec level. These observations suggest that, at least in these cases, the pre-existing suprathermal population does not play a significant role in the generation of the downstream high-energy tail of the momentum distribution. In the supra-thermal range a weak anisotropy (and low intensity) is measured within \(\sim 2\) hours before the arrival of highly-oblique shocks whereas strong anisotropy is found for the low-obliquity ones, due to ions streaming nearly-aligned to the magnetic field (Lario et al. 2019). In this context an investigation of the high-obliquity shocks with a measured large anisotropy might help shed light on the supra-thermal ions dynamics.

Localised enhancements at shocks, or shock spikes, have been identified in the past decades by a number of in-situ measurements via Explorer 33-35 (Armstrong et al. 1970) and Vela 4 (Singer & Montgomery 1971) in the supra-thermal (10s, 100s keV) ion intensity at the shock with duration of a few tens of seconds, \(\sim\) minutes (ACE, Lario et al. 2003). The Voyager-1 crossing of the solar termination shock (Decker et al. 2005) suggests a spike in high-energy protons (3.4 \(\sim 17.6\) MeV) and ions (40 \(\sim 53\) keV) intensities (Le Roux et al. 2007; Zuo & Feng 2013). The measured anisotropy makes spikes good candidate to improve our data-driven understanding of...
the role of the large scale magnetic geometry in the early-on particle acceleration.

Formerly postulated to originate from ions anisotropically reflected between Earth bow and IP shocks (Axford & Reid 1963), spikes were first modelled by Decker (1983) for quasi-perpendicular shocks \( \theta_{BN} > 70^\circ \), where \( \theta_{BN} \) is the angle between the local shock normal and the upstream unperturbed magnetic field) by using shock drift acceleration of a seed particle population. An alternative scenario of spikes originated as ions are reflected by the magnetic barrier and conserve the first adiabatic invariant applies to the quasi-perpendicular case only (Gieseler et al. 1999). Enhancements associated with \( \theta_{BN} < 70^\circ \), need an additional source of turbulence arguably provided by the self-excited waves produced by energetic ions streaming upstream (Scholer 1985).

Erdos & Balogh (1994) proposed that spikes are generated by magnetic trapping of particles formed by multiple crossings of the turbulent field lines with the shock surface: a suprathermal ion beam aligned with the upstream field would produce a single-peak PAD within the loss-cone. Erdos & Balogh (1994) thermal ion beam aligned with the upstream field would produce by magnetic trapping of particles formed by multiple crossings of turbulence arguably provided by the self-excited waves produced by energetic ions streaming upstream (Scholer 1985).

The present paper is devoted to the interpretation of the measured PADs and intensity of suprathermal ions in a recent STEREO/A (STA) quasi-perpendicular \( \left( \theta_{BN} \gtrsim 71^\circ \right) \) shock event 1992, DOY 256, shows a clear bimodal PAD (see Fig. 4. a, b therein) and estimates the length scale of the trapping region \( \gtrsim 10 \) times the suprathermal ions gyroradius.

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3 NUMERICAL SETUP

3.1 Synthesized turbulence

We carry out test-particle numerical simulations of super-thermal protons at a fast, planar collisionless shock travelling in a plasma with an embedded turbulent magnetic field. The upstream three-dimensional magnetic field is given by \( B(x) = B_0 + \delta B(x) \), with an average component \( B_0 \) having orientation \( \theta_{BN} \) with respect to the local shock normal and a random component \( \delta B = \delta B(x, y, z) \) having

**Figure 1.** Configuration of magnetohydrodynamic variables (adapted from Giacalone 2005; Fraschetti & Giacalone 2015) for the STA 2008 DOY 069 shock event (see Sect. 2). The red circle of radius \( r_c \) marks the effective area of the suprathermal particles detectors (see Sect. 3.2).
a zero ensemble average \( \langle \delta B(x) \rangle = 0 \); the turbulence is synthesized as superposition of plane waves with random amplitude, phase and orientation, with amplitudes determined by an assumed power spectrum (c.f. Decker & Vlahos 1986; Giacalone & Jokipii 1999; Fraschetti & Giacalone 2012). Simulations aiming at reproducing measurements of a single shock event can make use of one specific turbulence realization, rather than an ensemble average. We fit the PADs of H\( ^{+} \) within the time intervals \( U_{1}, U_{2}, D_{1} \), provided that the particle intensity satisfactorily reproduces the measured shape.

For the sake of simplicity, we assume the upstream three-dimensional magnetic turbulence to be isotropic and scale-invariant, with a Kolmogorov power spectrum, in the inertial range \([k_{0}, k_{max}]\), where \( k_{0} = 2 \pi / L_{c} \), \( L_{c} \) is the correlation length of the turbulence (Giacalone 2005; Fraschetti & Giacalone 2015). \( k_{max} \approx 2 \pi / L_{min} \) and \( L_{min} = 10^{-2} L_{c} \). At smaller wavenumbers, or larger scales, in the range \([k_{min}, k_{0}]\), where \( k_{min} = 2 \pi / L_{max} \) and \( L_{max} = 10^{2} L_{c} \), the power spectrum is assumed to be uniform. Such a power spectrum includes only the pre-existing SW fluctuations and not those "self-generated" by the energetic ions streaming ahead of the shock via, e.g., cyclotron-resonant streaming instability (Tademaru 1969; Lee 1983). In the simulations presented here, we set the unperturbed upstream magnetic field \( B_{0} = 5 \text{ nT} \) (see Sect. 2) and \( L_{c} = 0.01 \text{ AU} \), so that \( r_{g} / L_{c} \ll 1 \), where \( r_{g} \) is the particle gyroradius, at all particle energies considered here and the condition of resonant scattering with all turbulent wavenumbers is satisfied. The dataset for the STA 2008 DOY069 event (see Sect. 2) restricts the simulations parameter space to the power of the magnetic turbulence \( \langle \delta B^{2} \rangle \) relative to the power of the unperturbed field \( \langle B^{2} \rangle \). We have verified that a turbulence power spectrum extended to higher wavenumbers, or smaller scales, from \( 10^{-2} k_{0} \) up to \( 10^{3} k_{0} \) does not alter significantly the bi-modal shape of the PAD, nor the particle intensity.

The geometrical configuration implemented in the simulations is summarized in Fig. 1. The plane \( x = 0 \) marks the planar shock surface. Bulk plasma flows into the shock from \( x < 0 \) to \( x > 0 \) along the shock normal, along the \( x \)-axis. The components of the bulk flow velocity before and after the shock satisfy the jump conditions at an infinitely planar shock. The profile of the bulk velocity along the \( x \)-axis is chosen so that \( U_{0} \) lies on the \( xz \)-plane and \( U_{0} = (U_{0x}, 0, U_{0z}) = (147, 0, 185) \text{ km/s} \) (see Sect. 2).

The determination of the trajectory of individual particles by numerically solving the Lorentz equation in the prescribed magnetic field. Assuming that in the plasma rest frame both upstream and downstream electric field vanish (infinitely conductive), particles undergo acceleration by the motional electric field that writes in the shock frame \( E(x, y, z, t) = -U(x) / c \times B(x, y, z, t) \), where \( U(x) = (U_{x0}, U_{0y}, U_{0z}) \) and the magnetostatic field \( B(x, y, z, t) \) is passively advected along the flow (Giacalone & Jokipii 2009; Fraschetti & Giacalone 2015), where the \( t \)-dependence of \( B \) at a given location can be interpreted as a spatial variation as it results from the fluid advection only. Since the particles trajectories are integrated over a single turbulence realization, the phase-space distribution function in the time-intervals \( U_{1}, U_{2}, D_{1} \) represented here is not solution of a steady-state ensemble-average transport equation, as it corresponds to a particular realization of \( B \); the time variation of a chosen realization \( B \) at a given spatial location could average out with an equal and opposite time-variation at the same location of a distinct realization of \( B \) with no change for the ensemble average (see Sect. 5).

The boundary conditions are based on the approach in Giacalone (2005); Fraschetti & Giacalone (2015): the motion is tracked until either a) particles reach a pre-specified high-energy cut-off, taken to be much higher than the energy of interest in this study (\( p_{E} = 500 p_{0} \) where \( p_{0} \) is the injection momentum in the plasma frame), or b) particles escape by advection at a downstream boundary \( x_{p} = 2.5 \times 10^{9} (U_{0x} / U_{0y}) \), where the prescription of the return probability is implemented (Ellison et al. 1996; Giacalone 2005; Fraschetti & Giacalone 2015). No energy-independent free-escape boundary upstream is assumed. Ions are injected upstream on the plane \( z_{0} = r_{g}^{0} / 2 \), where \( r_{g}^{0} \) is the initial gyroradius, at a random location in the plane \( yz \) within a square of side \( L_{max} \) to capture the effect of the perpendicular transport due to the field line meandering that originates from scales larger than \( L_{c} \) (e.g. Jokipii 1966; Webb et al. 2009; Fraschetti & Jokipii 2011; Laitinen & Dalla 2017) with no ignorable coordinate (Jokipii et al. 1993; Jones et al. 1998). Particles are injected with an isotropic distribution in the local pitch-angle whose cosine is defined as \( \mu_{\text{local}} = p \cdot B / p B \), where \( p \) is the particle momentum in the local plasma frame.

3 For ions the PLASTIC geometric factor is 0.1 cm\(^{2}\)/sr (Table 1 in Galvin et al. 2008), for SEPT it is 0.17 cm\(^{2}\)/sr (Table 4 in Müller-Mellin et al. 2008).
4 RESULTS

We calculated PAD and intensity profiles for suprathermal protons in the PLASTIC and SEPT energy bands, respectively, for \( \sigma^2 = 0.1, 0.3, 0.4, 0.5, 0.7, 1.0, 1.2 \) for a number of magnetic turbulence realizations in each case. Given the PLASTIC supra-thermal energy band for \( \text{H}^+ \) (10 – 40 keV/nuc), the goldilocks injection particle energy in the local plasma frame, \( E_0 \), has to be lower than the low PLASTIC energy bound, 10 keV, to enable all particles to undergo shock-acceleration and resonantly interact with the upstream turbulence before accessing the PLASTIC energy band. In addition, the particle injection speed \( v_0 \) (in the upstream plasma frame) has to satisfy \( v_0/U_1^\ast \lesssim 10 \) as higher speed particles quickly isotropize downstream, as predicted by DSA. The value \( E_0 = 3 \text{ keV} \) (\( k_0, r_0 = 0.67 \)) satisfies such conditions and will be used hereafter.

Figure 2 compares the PADS during \( U1, U2 \) and \( D1 \) for distinct values of \( \Delta A < L_{\text{max}}/L_c \approx 10^2 \) with STA data. The expected and measured underlying monotonic upstream PAD (decreasing from \( \mu < 0 \) to \( \mu > 0 \)) due to reflected ions is found both during \( U1 \) and \( U2 \). The single realization of \( \sigma B \) shown here remarkably reproduces the bi-modal structure in \( U1 \) (Fig. 2, left panel, red curve) peaking at \( \mu \approx -0.4 \) and \( \mu \approx 0.0 \) with \( A = 20 \), due to particles streaming in low-scattering regime along the magnetic field lines (Erdos & Balogh 1994; Marhavila et al. 2003; Fraschetti & Giacalone 2015). The peak \( \mu \approx 0.0 \) is smeared out in the case of \( A = 50 \) (black curve), possibly due to broader range of angles between the local B and the local shock normal, captured by a larger collecting area (A), that enables isotropization of the PAD at \( \mu \approx 0.0 \). We note that the fit of the PAD during \( U1 \) only cannot constrain \( A \) due to the degeneracy introduced by the choice of a single turbulence realization: the combined fit of PADS in \( U2 \) and \( D1 \) allows one to reduce such a degeneracy with a larger degree of confidence.

As for \( U2 \) (Fig. 2, middle panel), the bi-modal structure seen in \( U1 \) is smeared out during \( U2 \), and simulations with \( A = 20 \) (green curve) well reproduce the monotonic trend; the transition from bi-modal to monotonic shape further upstream was emphasized in previous ensemble average calculations (Fraschetti & Giacalone 2015). A major difference between the two cases \( A = 20 \) and \( A = 50 \) is the intensity excess for \( A = 50 \) for \( \mu > 0.5 \) (even higher in our runs for \( A \gg 10^2 \)) due to the increase of the detector area (Sect. 3.2).

An additional difference between the cases \( A = 20 \) and \( A = 50 \) is the high reflected ions PAD of the latter for \( \mu < -0.5 \). A bending of \( f(\mu) \) as \( \mu \rightarrow -1 \) in \( U2 \) is suggested by the measured vanishing of \( f \) at \( \mu = -0.6 \) in \( U1 \), favouring the case \( A = 20 \); however, \( f(\mu < -0.5) \) is not constrained by data during \( U2 \). Finally, a bump in the case of \( A = 50 \) between \( \mu = 0.0 \) and 0.3 stands out over an underlying monotonic shape between \( \mu = -0.6 \) and 1. Such a bump might result again from the larger collecting area (larger A) that intersects a larger number of magnetic field lines crossing the shock with a higher chance of capturing a second stream of ions originating from a further region on the shock (\( U2 \) interval extends between \( \sim 6 \) and \( \sim 16 \) minutes upstream of the shock).

The right panel in Fig. 2 depicts the PAD during \( D1 \). The peak at \( \mu \approx 0.0 \) results from downstream advection of particles closely moving along magnetic field lines in a quasi-scatter-free scenario (Erdos & Balogh 1994; Fraschetti & Giacalone 2015). A difference

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4 We note that for the STA data (Yang et al. 2020) \( \mu \) is calculated in the SW frame, whereas the simulations use the local plasma frame; our tests show that this inertial-frame effect does not introduce an error significant to the data-fit, due to the coarse PLASTIC \( \mu \)-resolution.
between the cases $A = 20$ and $A = 50$ emerges only for $\mu < -0.75$, not constrained by data. Figure 3 shows STA/SEPT particles intensity in the 3 lowest suprathermal energy bands exhibiting an enhancement beyond compression at the shock arrival. During $U_2$ the intensity enhancement is well past; thus, strong deviations from monotonic PAD in $U_2$ are not to be expected. Figure 4 shows the simulated proton intensities profiles in the PLASTIC energy band $10 - 40$ keV (lower panel), and in the lowest SEPT energy band $84.2 - 92.7$ keV (upper panel), with parameters fixed by the PADs fit in Fig. 2 ($\sigma^2 = 0.3$ and $A = 20$) and no additional fitting. An enhancement at the shock in both panels, corresponding to the spike, seems to emerge. The intensity increase in the upper panel ($84.1 - 92.7$ keV) ahead of $U_2$ is lacking in the observations; however, we note that the turbulence realization is chosen to reproduce PAD and intensity during $U_1, U_2$ and $D1$ intervals only. The intensity before or past such intervals is affected by larger scale structure of the synthesized magnetic field.

**5 DISCUSSION AND CONCLUSION**

The length scale $\Delta x$ of the upstream magnetic trap originating the local intensity enhancement and the bi-modal anisotropy of $< 40$ keV/nuc protons ($r_g(40$ keV) $= 5$, 700 km in the upstream field) can be estimated as $\Delta x > \Delta t U_1 U_1^{-1} = 53,000$ km $\approx 9.3 r_g (40$ keV). For a scattering mean free path $\lambda < \Delta x \approx 10 r_g (40$ keV), the trap not only allows particles confinement, but also allows nearly scatter-free streaming along field lines that cross the shock in multiple points (the minimum value $\lambda = r_g$ is realized in stronger turbulence, i.e., $\sigma^2 > 1$, whereas we present here the case $\sigma^2 \sim 0.3$).

One caveat regarding our simulations is that we have used the magnetic obliquity inferred along the s/c trajectory crossing the shock over its detector area, whereas such an angle ($\theta_{Bn} = \mp 0^\circ$ for the 2009 DOY 69 event) can fluctuate, both in the spatial location and in time, along the shock surface due to its inherent corrugation (Neugebauer & Giacalone 2005; Koval & Szabo 2010; Ebert et al. 2016); multi-s/c IP shocks measurements reported fluctuations $\sim 15^\circ - 20^\circ$ over a scale $< 10^5 - 10^6$ km (ACE, Wind and Geotail, Terasawa et al. 2005) or down to $10^3$ km (Cluster, Kajić et al. 2019), confirmed by hybrid simulations for kinetic ions and fluid electrons (Kajić et al. 2019). Such a variability of $\theta_{Bn}$ does not alter our interpretation of magnetic trapping as a rippled shock surface propagating into a laminar medium has comparable confinement effects, as far as the ion scales are concerned, to a planar shock propagating into a turbulent field, as pre-existing turbulence corrugate the shock at scales much larger than electron-scales micro-instabilities and over longer time scales. Finally, the media upstream of Earth bow shock and IP shocks have been long measured to deviate from laminar structure, since Fairfield (1974), as a result not only of ions-generated waves but also of electrons-scale kinetic effect, such as energy exchange between electrons and ions mediated by large amplitude whistlers precursors (Wilson et al. 2017). Such scales needs kinetic ions-electrons particle-in-cell simulations and are therefore beyond the scope of this work.

We have neglected the electric field of the order of $v_A B/c$ arising from the magnetic field fluctuations modelled as Alfvén waves propagating along the field at speed $v_A$. This is justified by the fact that for the parameters used in our test-particle simulations, $v_A > v_A$ on both side of the shock. Stochastic acceleration, relevant as the particles move away from the shock, is expected to have a smaller effect on the spike formation because the electric field $v_A B/c$ is disordered and has therefore an average negligible effect (Fraschetti & Giacalone 2015).

An additional set of runs includes the PADs and intensity profiles of supra-thermal particles for a phase-space distribution function that solves the time-dependent equation of transport (Giacalone 2005); both the ensemble-averaged case and a few cases of single turbulence realization have been explored with the given turbulence power spectrum. Such cases do not provide a significantly better fit of PADs $U_1, U_2$ and $D1$ and are therefore not shown here.

The turbulence upstream the shock is modeled herein as a superposition of plane waves with random amplitude, phase and orientation and is described by the power spectrum via normalisation ($\sigma^2$) and power law index within the inertial range ($11/3$). In the past decade the interpretation of 3D large-scale magnetohydrodynamic numerical simulations and of in-situ measurements has advocated the role of current sheets, or more generally of large gradients of the magnetic field such as discontinuities, in driving turbulence (Matthaeus et al. 2015), for example, in the SW (Greco et al. 2016). Dropouts in solar energetic particles count rates suggest crossing by the s/c of particle-filled flux tubes bounded by discontinuities and adjacent to particle-voided flux tubes (Mazur et al. 2000); such dropouts can be measured if the flux tube are magnetically connected with the solar photosphere and map its super-granulation (Giacalone et al. 2000), assuming a negligible cross-field diffusion. In an alternative scenario, if time dependence of perpendicular diffusion is included (e.g., Fraschetti & Giacalone 2012) dropouts are consistent with observations provided that the diffusion coefficient becomes large afterward (Laitinen et al. 2013). An inspection of the 1/8 second resolution magnetic field vector components/magnitude time series of the 2008 DOY 069 event (IMPACT/MAG) within 16 minutes ahead and past the shock shows no evidence of discontinuities (large fluctuations or sharp changes of direction), although a statistical analysis following, e.g., the criteria of Burlaga (1969) on rotation of the B-field $> 30^\circ$ or of Tsurutani & Smith (1979) on $\partial B / B > 0.5$ to identify discontinuities has not been carried out. Consistently, no impulsive voids, or dropouts, in the count rate of supra-thermal particles were observed in PLASTIC or SEPT. Thus, data suggest that the turbulence in the proximity of the shock event

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[Figure 4. Simulated proton intensities (lower panel) in the PLASTIC energy band $10 - 40$ keV, and (upper panel) in the lowest SEPT energy band ($84.2 - 92.7$ keV, cf. Fig. 3) with $\sigma^2 = 0.3$ and $A = 20$. The lower x-axis is in units of injection gyroradius, the upper x-axis in units of time in the s/c frame and the y-axis is normalized to an estimated downstream intensity. The vertical red line marks the shock passage and the green dashed lines bound the three time windows as labelled in Yang et al. (2020).]
the turbulence as plane waves superposition with an upper bound-
dence of reconnecting current sheets. Therefore, a representation of
turbulence. As aforementioned, data do not show significant evi-
dations and cannot be neglected in the time evolution of the
numerically analysed. In the latter case, reconnecting current sheets
as coherent structures) can mix with large amplitude magnetic
fluctuations and cannot be neglected in the time evolution of the
turbulence. As aforementioned, data do not show significant evi-
dence of reconnecting current sheets. Therefore, a representation of
the turbulence as plane waves superposition with an upper bound-
ary $\sigma^2 \sim 1$ is expected to provide a realistic representation of the
turbulence crossed by the STA 2008 DOY 069 shock. However, we
note that, since the spacecraft probes the SW only along its trajec-
ory, the role of current sheet in the turbulence crossed by the shock
over its entire spatial extent cannot be ruled out, even in regions of
the shock magnetically connected with the s/c; however, due to the
lack of evidence, it is not included herein. The interplay of current
sheets and shocks in the acceleration of particles has been analyzed
in several recent works (Matsumoto et al. 2015; Zank et al. 2015; le
Roux et al. 2016; Zhao et al. 2019): the interaction of the shocks
with current sheets can generate magnetic islands thereby energiz-
ing particles. However, owing to the reasons outlined above, for the
STA 2008 DOY 069 event current sheets are not a dominant effect in
the particle acceleration.

In summary, we have carried out test-particle simulations for
protons accelerated at a laminar highly-oblique shock propagating
into a medium with an embedded pre-existing turbulence to explain
data for the STEREO quasi-perpendicular fast reverse shock of a
stream interaction region 2008, DOY 069 (March 9th, UT: 19:50).
We have shown that the main features of PADS and of intensity pro-
files of suprathermal protons ($10−40$ keV and $84.1−92.7$ keV) mea-
sured within $10$ (downstream) 16 (upstream) minutes from the shock
are reproduced with excellent accuracy. The upstream bi-modal
structure of PADS, due to bi-directional streaming of nearly scatter-
free protons, can be hardly accounted for by shock-reflected ions
ions, and its smearing-out further upstream, emerges clearly and
consistently with earlier works (e.g., Erdos & Balogh 1994). A
systematic search of spikes at IP shocks is therefore needed to
clarify whether or not PAD bi-modality is more likely to emerge at
high-obliquity shocks as early models suggest (Decker 1983) or is
also found at shocks with small obliquity propagating into highly
turbulent SW. The prospect of measuring with Parker Solar Probe
and Solar Orbiter a larger number of weak events close to the Sun
with a very steep momentum spectrum (not many high energy par-
icles) as compared to 1 AU will help shed light on the role of $10^2−10^3$ km-scale of the magnetic structure in early-on phase of
the particles acceleration at shocks.

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DATA AVAILABILITY

The STEREO/SEPT data underlying this article are publicly avail-
able at http://www2.physik.uni-kiel.de/stereo/index.php?doc=data.
The 1/8 seconds resolution IMPACT/MAG data are publicly avail-
able at https://cdaweb.gsfc.nasa.gov/cgi-bin/eval3.cgi. The numerical
code will be shared on reasonable request to the corresponding
author.

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