Energetic particle pressure in intense ESP events

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Abstract. We study three intense energetic storm particle (ESP) events in which the energetic particle pressure $P_{EP}$ exceeded both the pressure of the background thermal plasma $P_{th}$ and the pressure of the magnetic field $P_B$. The region upstream of the interplanetary shocks associated with these events was characterized by a depression of the magnetic field strength coincident with the increase of the energetic particle intensities and, when plasma measurements were available, a depleted solar wind density. The general feature of cosmic-ray mediated shocks such as the deceleration of the upstream background medium into which the shock propagates is generally observed. However, for those shocks where plasma parameters are available, pressure balance is not maintained either upstream of or across the shock, which may result from the fact that $P_{EP}$ is not included in the calculation of the shock parameters.

1. Introduction
The highest intensities of solar energetic particles (SEPs) in a solar cycle are usually observed in association with the passage of interplanetary shocks [1]. The particle enhancement associated with the passage of interplanetary shocks is commonly known as an Energetic Storm Particle (ESP) event because of its association with the occurrence of sudden storm commencements [e.g., 2]. If the energy density of SEPs observed around the passage of the shocks becomes comparable to those of the background fields and plasma particles, the effects that such intense energetic particle populations exert on the shocks are not negligible. Such situations are usually described in terms of “cosmic-ray modified” shocks [3, 4, 5, 6, 7, 8, 9] where the effects produced by the energetic particles include the deceleration of the medium where the shock propagates and non-linear effects on the processes of particle acceleration [e.g., 4].

In steady state, the mass and momentum flux conservation relations across the shocks can be written as $\{\rho_m U_m\}_0=0$ and $\{\rho_m U_m (U_m^2 + P + B^2/2\mu_0)\}_0=0$ where $\{\}$ denotes the difference of the enclosed quantity between the two sides of the shock, $\rho_m$ is the mass density, $U_m$ is the normal component relative to the shock surface of the flow velocity $U$ measured in the shock rest frame, $B_i$ is the component of the magnetic field vector tangential to the shock surface, and $P$ is the particle pressure, which usually is assumed to be isotropic [10]. It is also usually assumed that the only contribution to the particle pressure $P$ comes from the thermal particles computed as $P_{th}=n_p k T_p + n_e k T_e$ where $k$ is the Boltzmann’s constant, $n_p$ and $n_e$ is the number density, and $T_p$ and $T_e$ the temperature of the proton and electron.

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populations forming the background thermal plasma, respectively. However, there are a number of distinct periods and/or regions of interplanetary space when the pressure exerted by the non-thermal energetic particles is comparable to or even exceeds both $P_{\text{th}}$ and the magnetic field pressure, $P_B = B^2/2\mu_0$ [11, 12, 13, 14]. Therefore, it is necessary to include in $P$ the non-negligible contribution of the pressure exerted by the non-thermal energetic particles $P_{\text{EP}}$ and use $P = P_{\text{EP}} + P_{\text{th}}$ [15].

In this article we compare three cases where $P_{\text{EP}}$ exceeded $P_B$ by more than one order of magnitude and (when plasma observations were available) $P_{\text{EP}}$ exceeded also $P_{\text{th}}$. One of these three cases occurred during the most intense SEP event of solar cycle 22 [11] and the remaining cases during the most intense events observed by the spacecraft A of the Solar Terrestrial Relations Observatory (STEREO-A) in solar cycle 24. The highest particle intensities were reached around the passage of interplanetary shocks. The peculiarity common to these three events is the presence of a foreshock region containing decreased magnetic field strength and, when plasma observations are available, depleted solar wind density and gradual increase of solar wind speed. We discuss whether these shocks can be classified as cosmic-ray mediated shocks.

2. Observations

Figure 1 shows hourly averages of (a) 4-6 MeV and (b) 25-53 MeV proton intensities measured by the Low Energy Telescope (LET) [16] and the High Energy Telescope (HET) [17] of the IMPACT (In-Situ Measurements of Particles and CME Transients) investigation [18] on board STEREO-A. The time interval spans from day 1 of year 2009 to day 243 of year 2014. The red circle indicates the highest 25-53 MeV proton intensity over this time interval, whereas the blue circle indicates the highest 4-6 MeV proton intensity. The highest 25-53 MeV proton intensity was observed on day 205 of 2012 [13], while the highest 4-6 MeV proton intensity occurred on day 149 of 2012. These two events were observed in association with the passage of interplanetary shocks and we will show that their properties are comparable to the most intense event observed in solar cycle 22 on day 293 of year 1989 [11].

![Figure 1](image-url)

**Figure 1.** Hourly averages of (a) 4-6 MeV proton intensities measured by STEREO-A/LET [16] and (b) 25-53 MeV proton intensities measured by STEREO-A/HET [17]. The red and blue circles indicate the maximum 25-53 MeV and 4-6 MeV proton intensities measured by STEREO-A in solar cycle 24, respectively.
Figure 2 shows from top to bottom (a) energetic proton intensities observed by (left) the Energetic Particle Sensor (EPS) on board the Geostationary Operational Environmental Satellite-7 (GOES-7) [19] on day 293 of 1989, (center) by STEREO-A/HET [17] on day 205 of 2012 and (right) by STEREO-A/HET on day 149 of 2012, (b) magnetic field magnitude measured by (left) the Goddard Space Flight Center (GSFC) magnetometer on board the Interplanetary Monitor Platform-8 (IMP-8) [20] and (center, right) the Magnetic Field Experiment of the IMPACT suite of instruments [21] on board STEREO-A, (c) solar wind proton density, (d) solar wind proton temperature, and (e) solar wind speed as measured by (left) the Massachusetts Institute of Technology (MIT) Faraday Cup on board IMP-8 [20] and (center, right) by the Plasma and Suprathermal Ion Composition sensor (PLASTIC) on board STEREO-A [22]. Figure 2f shows the magnetic field pressure $P_B$ (red symbols), the solar wind thermal pressure $P_{th}$ (blue symbols), and the energetic particle pressure $P_{EP}$ computed over the indicated energy interval (black trace). In the computation of $P_{th}=n_p kT_p + n_e kT_e$ we have assumed neutrality ($n_p=n_e$) and $T_e=2T_p$ based on statistical surveys of proton and electron temperatures in post-shock plasmas [23]. The computation of $P_{EP}$ and its limitations due to the finite energy range of the energetic particle observations are described in detail in the Appendix.

Figure 2. The three most intense ESP events in solar cycle 22 as observed near-Earth (left) and in solar cycle 24 as observed by STEREO-A (center and right panels). From top to bottom we show: (a) proton intensities at the indicated energy, (b) magnetic field strength, (c) solar wind proton density, (d) solar wind proton temperature, (e) solar wind speed, (f) energetic particle pressure (black trace), magnetic field pressure (red symbols) and thermal pressure (blue symbols), for the events on day 293 of 1989 (left), 205 of 2012 (center) and 149 of 2012 (right). See text for details.
The solid vertical lines in Figure 2 (labelled with the symbol S) indicate the passage of interplanetary shocks associated with these intense particle events. The vertical dotted lines in Figure 2 indicate the onset of a depression in magnetic field strength that coincides with an increase of the energetic particle intensities before the arrival of the shock. In the first two events (1989/293 and 2012/205) the decrease of magnetic field and increase of energetic particle intensities occurred abruptly, whereas in the event on 2012/149 the particle increase occurred more gradually, peaking at the arrival of the shock. The periods between the dotted and the solid vertical lines were dominated by $P_{\text{EP}}$, exceeding $P_{\text{B}}$ by two orders of magnitude in the events on 1989/293 and 2012/205 and only by one order of magnitude in the event on 2012/149. The dashed vertical lines in the left and center panels of Figure 2 indicate a prior increase of magnetic field magnitude, solar wind density and solar wind temperature that could be associated with the passage of an earlier weak shock [11, 13].

There are a number of similarities between the three events of Figure 2: (1) the increase in the energetic particle intensities before the shock passage coincides with a decrease of the magnetic field magnitude (indicated by the vertical dotted line), (2) the period before the arrival of the shock is characterized by a steady increase of the solar wind speed $V_{sw}$, (3) with the exception of the event on 2012/205 where solar wind plasma observations are not available, the period of depleted magnetic field is also characterized by a rarefied solar wind density, (4) the energetic particle pressure $P_{\text{EP}}$ exceeded $P_{\text{B}}$ over the period between the dotted and the solid vertical lines, of ~195 minutes during the event on 1989/293, ~96 minutes during the event on 2012/205, and ~60 minutes during the event on 2012/149, (5) with the exception of the event on 2012/205 where $P_{\text{in}}$ could not be computed, $P_{\text{EP}}$ also exceeded $P_{\text{in}}$ in the events on 1989/293 and 2012/149 events. However, whereas the event on 1989/293 showed a decrease of $T_p$, in the event on 2012/149 $T_p$ increased, and (6) behind the shock $P_{\text{B}}$ and $P_{\text{in}}$ dominated $P_{\text{EP}}$ throughout the post-shock compressed plasma.

It is possible that the process responsible for the depletion of the magnetic field strength as the energetic particle intensity increased before the arrival of the shock is similar to that proposed for the formation of diamagnetic field cavities observed upstream of the Earth’s bow shock [e.g., 24]. Beams of energetic particles propagating away from the shock may generate a diamagnetic current that weakens the background magnetic field. The result is the creation of a crater of tenuous plasma and weak magnetic field bounded by enhanced densities and field strengths [25]. The hot compressed plasma left behind the shock, however, does not allow the creation of these cavities by particles propagating in the downstream region of the shocks. These cavities are therefore only observed in the upstream region of the shocks when the intensity of energetic particles is large enough to create enough pressure to depress the foreshock magnetic field strength and plasma density.

3. Can these shocks be classified as cosmic-ray mediated shocks?

The basic observational features of cosmic-ray mediated shocks are (1) a decrease of the upstream plasma flow $U_n$ in the shock rest frame due to the pressure gradient of the particles ahead of the shock decelerating the background medium, and (2), in steady state, a pressure balance observed in the upstream region of the shock when $P_{\text{EP}}$ is included in the estimation of the total pressure [5, 8, 9]. This pressure balance can be also evaluated across the shock by checking if $\{\rho_m U_n^2 + P + B_n^2/2\mu_0\}=0$ [10]. Figure 2c shows that the solar wind speed $V_{sw}$ in the observer’s frame steadily increased before the passage of the shock in the three events (especially in the region between the vertical dotted and solid lines). This increase of $V_{sw}$ translates into a decrease of the plasma flow $U_n$ in the shock frame of reference [8, 9] if the shock speed $V_{\text{shock}}$ is constant.

In order to precisely estimate $U_n$, it is necessary to accurately compute both the shock speed and the direction of the normal to the shock. The formulae usually used to compute the shock parameters (i.e. the Rankine-Hugoniot conservation conditions) conventionally neglect the energetic particle contribution to the total pressure. Of the three events depicted in Figure 2, only the one with the complete set of plasma parameters, including the components of the solar wind velocity (the 2012/149 event), allows us to compute the shock parameters.
Figure 3. (a) One-minute averages of 14.9–17.1 MeV proton intensities, (b) magnetic field strength, (c) solar wind proton density, (d) solar wind speed $V_{sw}$ and plasma flow speed in the shock frame of reference, (e) energetic particle pressure $P_{EP}$ over the indicated energy range (black trace), thermal plasma pressure $P_{th}$ (blue symbols), $B_t^2/2\mu_0$ (red symbols), $P_{ram}$ (green symbols) and $P_{SUM}=\rho mU_n^2+P_{th}+P_{EP}+B_t^2/2\mu_0$ (purple symbols). Whereas there is a flow deceleration in front of the shock passage, there is no total pressure balance across the shock. See text for details.

We have applied the method described in [26] to compute the shock parameters of the shock on day 149 of 2012 (note that energy conservation equation was not considered in the computation of the shock parameters). The asymptotic solutions of this model provide the following parameters: normal to the shock in the RTN coordinate system $n=(0.98,-0.17,-0.03)$, shock speed along the normal $V_{shock}=706 \pm 38$ km s$^{-1}$, angle between the upstream magnetic field and the normal to the shock $\theta_{Bn}=76^\circ$, Alfvénic Mach number=8.7, magnetic field compression ratio=6.8 and density compression ratio=9.0. Once we know the normal to the shock and the shock speed, we proceed to compute $U_n=V_{sw} \cdot n-V_{shock}$, the ram pressure $P_{ram}=\rho mU_n^2$ and the quantity $P_{SUM}=\rho mU_n^2+P_{th}+P_{EP}+B_t^2/2\mu_0$. Figure 3 shows from top to bottom (a) 14.9–17.1 MeV proton intensities, (b) magnetic field magnitude, (c) solar wind proton density $n_p$, (d) solar wind speed $V_{sw}$ (blue trace) and the flow speed $U_n$ (gray trace), (e) the thermal pressure $P_{th}$ (blue symbols), the energetic particle pressure $P_{EP}$ over the indicated energy range (black trace), $B_t^2/2\mu_0$ (red symbols), the ram pressure $\rho mU_n^2$ (green symbols) and the quantity $P_{SUM}$ (purple symbols). Figure 3d shows that around the time of the particle intensity enhancement (indicated by the vertical dotted line), $U_n$ decreases by about $\sim 100$ km s$^{-1}$. However just before the arrival of the shock, as high-energy proton intensities ceased increasing, $U_n$ stopped decreasing.
Throughout the upstream region of the shock $P_{\text{ram}}$ dominated over $P_{\text{EP}}$, $P_{\text{th}}$, and $P_{\text{B}}$, whereas downstream of the shock $P_{\text{th}}$ contributed the most to $P_{\text{SUM}}$. As the shock approached the spacecraft and $P_{\text{EP}}$ started exceeding both $P_{\text{th}}$ and $P_{\text{B}}$, the deceleration of the plasma flow and the density depletion observed at the time of the vertical dotted line yielded to a decrease of $P_{\text{ram}}$ for the whole period comprised between the vertical dotted and solid lines in Figure 3. It is clear that before and across the passage of the shock, $P_{\text{SUM}}$ is not constant (in particular at the time of the vertical dotted line). Possible reasons for this lack of balance of the quantity $P_{\text{SUM}}$ include the following:

1. Due to the limited energy coverage of the particle instruments, our calculated $P_{\text{EP}}$ is only a lower limit (see Appendix A). If the depleted region of $P_{\text{SUM}}$ observed before the shock were due to <83 keV protons, then to fill the depletion would require the intensity of this region to be very high, have a very steep energy spectra, and be localized only in that region (see Appendix A). It would follow that this population, presumably accelerated at the shock, be present also in the downstream region of the shock, but in such a manner that $P_{\text{SUM}}$ would have to remain constant across the shock.

2. The observed depletion in $P_{\text{SUM}}$ is a consequence of the depletion in $P_{\text{ram}}$, the dominant pre-shock contribution to $P_{\text{SUM}}$, which derives from the decrease of $U_n$ and low values of $n_p$. An error in the estimates of any of these terms implies an error in the evaluation of $P_{\text{ram}}=\rho\frac{m}{2}U_n^2$. In particular, the evaluation of $U_n$ requires an accurate computation of the shock speed and the shock normal. These shock parameters were derived as an asymptotic solution of the Rankine-Hugoniot conditions that did not include the effects of the energetic particles. However, since we argue that $P_{\text{EP}}$ plays a significant role determining the shock parameters, we have an inconsistency that must be addressed in future calculations.

3. The spatial structure of the shock may not have been steady due to its instability to, for example, sound waves incident from the upstream medium [27], magnetic waves propagating oblique to the average magnetic field [28], and amplification of Alfvén waves by cyclotron resonant interaction with shock accelerated particles [8]. Whereas these fluctuations may lead to the unbalance of $P_{\text{SUM}}$, it is difficult to explain the deep depletion of $P_{\text{SUM}}$ before the shock via only fluctuations of $U_n$ and $n_p$. It is also possible that the high $P_{\text{EP}}$ could result from the passage of the spacecraft through a ripple or indentation on the shock surface (~0.01 AU in depth implied by a 1-hour duration and $V_{sw}\sim400$ km s$^{-1}$) that could temporarily trap and enhance intensities of high energy protons able to reflect from two magnetic connection points at the quasi-perpendicular shock while low energy ions were simply transmitted through the shock [e.g., 29]. Therefore, of the basic features of cosmic-ray mediated shocks pointed out by Terasawa et al. [8, 9], we see a relative decrease of $U_n$ in the foreshock region as energetic particle intensities increase, but not a balance of $P_{\text{SUM}}$.

4. Conclusions
The highest energetic particle intensities observed in solar cycle 22 close to Earth and by STEREO-A in solar cycle 24 occur in association with interplanetary shocks. The upstream region of these shocks was characterized by a decrease of the magnetic field strength coinciding with the last increase of energetic particle intensities and, when plasma observations are available, with a depletion of solar wind density. During these periods the pressure exerted by the energetic particles $P_{\text{EP}}$ exceeded the magnetic field pressure $P_{\text{B}}$ and the pressure of the background thermal particles $P_{\text{th}}$. These shocks showed also a steady increase of $V_{sw}$ that translates into a decrease of the plasma flow speed in the shock frame of reference as a result of the pressure of the energetic particles reflected ahead of the shock. For the event on day 149 of 2012, when the completeness of plasma parameters allows us to compute shock parameters, we did not observe a total pressure balance. Apparently, the accurate computation of the shock parameters must consider the effects of $P_{\text{EP}}$ on the structure of the shocks.
5. References

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Appendix A. Computation of energetic particle pressure $P_{EP}$

The expression used to compute the pressure exerted by the energetic protons is

$$P_{EP} = \left( \frac{4 \pi}{3} \right) \left( \frac{2m}{T_2} \right)^{1/2} \int_{T_1}^{T_2} dT \frac{T^{1/2}}{j(T)} ,$$  \hspace{1cm} (1)$$

where $m$ is the proton mass, $j(T)$ is the differential proton flux at the reference energy $T$, and $T_1$ and $T_2$ are the boundaries over which we evaluate the pressure $P_{EP}$ [11]. Strictly speaking, this expression should be evaluated in the plasma frame [15], but since our lower limit for the proton energies is $\sim 83$ keV (corresponding to a proton velocity of $v \sim 4000$ km s$^{-1}$), the expression in the spacecraft frame approximates the correct partial pressure of energetic particles to the order of $O(U/v) < 0.10$.

Figure A1 shows the computation of $P_{EP}$ for the event on day 149 of 2012. Figure A1a shows the proton intensities measured by the combination of particle instruments on board STEREO-A (i.e. the Solar Electron and Proton Telescope (SEPT) [30], the Low Energy Telescope (LET) [16] and the High Energy Telescope [17]). Figure A1b shows the proton energy spectra at the time of the shock passage (indicated by the solid vertical line in Figure A1a). The differential particle intensities $j(T)$ at each energy channel are indicated by the colored symbols in Figure A1b. We use the mathematical expression $\log[j(T)] = a + b \log T + c T$ (solid black line in Figure A1b) to fit the energy spectra over the energy range 83 keV – 60 MeV.

Owing to the limited energy coverage of the energetic particle instruments, one must wonder about the contribution to $P_{EP}$ of both the most abundant low-energy protons below 83 keV and the protons of energies above 60 MeV. We have assumed several dependences for the energy spectra below 83 keV, from the simple extrapolation of the fitted spectra (indicated by the dashed thick black line in Figure A1b) to power-law functions as $T^{0}$, $T^{0.5}$, $T^{1.0}$, $T^{1.5}$, $T^{2.0}$, $T^{3.0}$ indicated by the orange, purple, cyan, blue, green and red dotted lines in Figure A1b, respectively. Figure A1c shows the integrand of equation (1) at the time of the shock passage. Figure A1d shows how the integrated pressure depends on the maximum energy $T_2$ of the integration range. The solid thick line considers as lower boundary $T_1$ the minimum proton energy measured by STEREO-A/SEPT ($T_1$=83 keV) and the spectra fitted in Figure A1b. The dotted lines and the dashed thick line of Figure A1d assume a lower boundary $T_1$=4 keV and the extrapolations of the energy spectra to lower energies depicted in Figure A1b. The error in the particle pressure is of the order $O(U/v) = 0.5$ near 4 keV, but its contribution to the pressure $P_{EP}$ over the whole energy range is negligible except for the steepest spectrum. Figure A1d also shows that above $\sim 10$ MeV, $P_{EP}$ seems to saturate, suggesting that the contribution of the higher energy particles can be considered negligible.

Finally, Figure A1e shows the evolution of $P_{EP}$ around the shock passage considering the individual one-minute spectra throughout the time interval considered in Figure A1a. Whereas the solid black line represents the fitted energy spectra over the energy range $T_1=83$ keV and $T_2=60$ MeV, the dotted and dashed lines represent the extrapolation of the energy spectra to lower energies (up to $T_1=4$ keV) as depicted in Figure A1b. The contribution of the low-energy portion becomes significant for steep energy spectra (e.g., case $T^{1.0}$) and when the low-energy proton intensities are already elevated (e.g. in the downstream region of the shock).
Figure A1. (a) One-minute averages of the proton intensities measured by STEREO-A/SEPT, LET and HET for the ESP event observed on day 149 of 2012. (b) Energy proton spectra at the time of the shock passage over the energy range 83 keV - 60 MeV. The solid black line assumes a dependence $\log[j(T)] = a + b \log T + cT$ whereas the dotted and the dashed black thick lines assume different dependences to extrapolate the energy spectra down to 4 keV. (c) Energy dependence of the integrand of equation (1) at the time of the shock passage. (d) Dependence of $P_{EP}$ on the maximum energy $T_2$ of the integration ranges. (e) Time evolution of $P_{EP}$ computed over the energy range 83 keV – 60 MeV (solid black line) and over the energy range 4 keV - 60 MeV assuming the extrapolations of the energy spectra to lower energies depicted in panel (b) (dotted and dashed lines). See text for details.