Large Energetic Particle Pressures in Solar Cycles 23 and 24

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Abstract. We study periods of elevated energetic particle intensities observed at the L1 Sun-Earth Lagrangian point when the partial energy density associated with energetic (≥80 keV) particles (P_{EP}) dominates that of the local magnetic field (P_B) and thermal plasma populations (P_{PLS}). These periods are not uncommon and are frequently observed prior to the passage of interplanetary (IP) shocks. Because of the significant decreases in key solar wind parameters observed during solar cycle 24 [e.g., 1], we were motivated to perform a comparative statistical analysis to determine if the occurrence rate of periods when P_{EP} exceeded P_B or P_{PLS}, or both, differed between solar cycles 23 and 24. We find that the general decrease of P_B and P_{PLS} in solar cycle 24 was also accompanied by a general decrease of periods with elevated P_{EP}. The result is that solar cycle 24 showed a lower number of time intervals dominated by P_{EP}. We analyze whether these differences can be related to the properties of the IP shocks observed at L1. Incomplete datasets of shock parameters do not show significant differences between solar cycles 23 and 24 that would allow us to explain the difference in the number of periods with P_{EP}>P_B and P_{EP}>P_{PLS}. We analyze then the averaged plasma parameters measured in the upstream region of the shocks and find significantly lower solar wind proton temperatures and magnetic field magnitude upstream of IP shocks in solar cycle 24 compared with those in solar cycle 23. These factors, together with the lower level of solar activity, may explain the lower particle intensities in solar cycle 24 and hence the fewer events with P_{EP}>P_B and P_{EP}>P_{PLS}.

1. Introduction

Magnetohydrodynamic studies of solar wind structures generally assume that the pressure exerted by energetic particles is negligible compared to both (1) the hydrostatic magnetic field pressure computed as P_B = B^2 / 2\mu_0 (where B is the magnetic field intensity and \mu_0 is the magnetic permeability), and (2) the pressure exerted by the solar wind thermal particles P_{PLS}, usually computed as P_{PLS} = n_p k T_p + n_e k T_e (where k is the Boltzmann constant, n_p the solar wind proton density, n_e is the solar wind electron density, T_p the solar wind proton temperature, T_e the solar wind electron temperature, and where the contribution of alpha particles and heavier ions is assumed negligible). However, there have been a number of reports showing distinct periods and/or regions of interplanetary (IP) space when the partial
pressure exerted by energetic particles $P_{EP}$ is locally comparable to or even exceeds both $P_B$ and $P_{PLS}$ [e.g., 2, 3, 4, 5, 6, 7, 8]. In particular, Lario et al. [7] analyzed periods observed by STEREO-A at ~1 AU during the rising and maximum phases of solar cycle 24 when the pressure exerted by $\geq 83$ keV protons was larger than $P_B$. These periods occur predominantly in association with the passage of IP shocks when depressed magnetic field in the upstream region of the shocks coincides with increases of energetic particle intensities. Occasionally, periods when $P_{EP}$ exceeds $P_B$ may also occur when solar energetic particles (SEPs) are injected into regions of depressed magnetic field, although the occurrence of these periods is much more infrequent than those associated with IP shocks.

The observation of periods with $P_{EP} > P_B$ and $P_{EP} > P_{PLS}$ depends on both the existence of intense sources of energetic particles (such as strong IP shocks) and the properties of the background medium where these particles propagate. Compared to previous solar cycles, the first part of solar cycle 24 showed a significant drop in the solar wind output with significant decreases in solar wind speed $V_{sw}$, proton density $n_p$, proton temperature $T_p$, thermal pressure $P_{PLS}$, and magnetic field magnitude $B$ [1, 9]. Under the assumption that energetic particle intensities in both solar cycles are similar, the decline observed in the solar wind parameters may translate into more frequent observations of periods with $P_{EP} > P_B$ and $P_{EP} > P_{PLS}$. On the other hand, the medium where IP shocks propagate may also have important implications for the strength of the IP shocks arriving at 1 AU, and hence their capability to accelerate particles. In this article we analyze how the frequency of periods dominated by the pressure exerted by energetic particles has varied over the last two solar cycles and try to find possible explanations in terms of the shock strength and the IP medium where these shocks propagate.

![Figure 1. Hourly averages of (a) 1.89-4.75 MeV proton intensities measured by ACE/EPAM/LEMS120, (b) the pressure $P_{EP}$ exerted by protons in the energy range 83-2000 keV, (c) magnetic field pressure $P_B$, (d) solar wind thermal pressure $P_{PLS}$, (e) the ratio between $P_{EP}$ and $P_{PLS}$, and (f) the ratio between $P_{EP}$ and $P_B$. The horizontal straight line in (a) indicates the differential intensity above which $P_{EP}$ has been computed. The horizontal straight lines in (e) and (f) indicate the values $P_{EP}/P_{PLS}=1$ and $P_{EP}/P_B=1$, respectively.](image-url)
2. Frequency of events with $P_{EP}>P_B$ and $P_{EP}>P_{PLS}$

Figure 1 shows from top to bottom and over the time interval from day 242 of 1997 to day 243 of 2016 hourly averages of (a) 1.89–4.75 MeV ion differential intensities measured by the LEMS120 telescope of the EPAM instrument [10] on board the Advanced Composition Explorer (ACE); (b) $P_{EP}$ computed over the energy interval 83–2000 keV; (c) $P_B = B^2/2\mu_0$; (d) $P_{PLS} = n_e k(T_T + T_e)$ (computed assuming $T_e = 2 T_p$, [e.g., 11]); (e) the ratio $P_{SP}/P_{PLS}$; and (f) the ratio $P_{EP}/P_B$. Solar wind parameters $B$, $n_e$, $T_p$ in Figure 1 come from OMNI data sets at spdf.gsfc.nasa.gov/pub/data/omni/low_res.omni/.

Energetic particle pressure $P_{EP}$ in Figure 1 was computed as

$$P_{EP} = \left(\frac{4\pi}{3}\right) (2m_p)^{1/2} \int_{E_1}^{E_2} E^{1/2} j(E) dE$$

where $E$ is the proton kinetic energy, $j(E)$ is the proton differential flux, $m_p$ is the proton mass, and $E_1$ and $E_2$ are the limits of the energy range over which $P_{EP}$ is computed (in this case $E_1=83$ keV and $E_2=2000$ keV). Since ACE/EPAM/LEMS120 does not distinguish ion species, we have used hourly averages of the differential particle intensities measured by ACE/EPAM/LEMS120 to determine $j(E)$, assuming that heavy ions make a negligible contribution into the measured particle intensities. A functional form described as a power law with an exponential cutoff over the energy range 83–2000 keV has been fitted to $j(E)$ measured in the energy channels of ACE/EPAM/LEMS120. When doing this fit we have considered only those points where the differential intensity of the energy channel 1.89–4.75 MeV was above 0.06 particles (cm$^2$ s sr MeV)$^{-1}$, as indicated by the horizontal line in Figure 1a. This intensity threshold allowed us to consider only cases where intensities were above the instrumental background and the energy spectra over the differential energy channels of ACE/EPAM/LEMS120 were well fitted by the chosen functional form. The horizontal solid lines in Figures 1e and 1f indicate the values $P_{EP}/P_{PLS} = 1$ and $P_{EP}/P_B = 1$, respectively. Periods with $P_{EP}>P_B$ and $P_{SP}>P_{PLS}$ were frequently observed, and most of them occurred in association with the arrival of shocks accompanied by elevated particle intensities.

In order to estimate the frequency distribution of time intervals with elevated particle intensities, we have computed the number of hourly data points falling within different ranges of particle intensities. This technique (explained in detail elsewhere [e.g., 12]) consists of dividing the particle intensity data points displayed in Figure 1a in equally logarithmic spaced bins and computing the number of data points in each bin. Figure 2a shows the number of hourly averaged data points from the time series plotted in Figure 1a that fall in each of the equally logarithmic-spaced intensity bins for the time interval between day 242 of 1997 to day 4 of 2008 (Fig. 2a) and from day 4 of 2008 to day 243 of 2006 (Fig. 2b). The first time interval covers most of solar cycle 23 whereas the second covers most of solar cycle 24. We have arbitrarily considered that the division between the two solar cycles occurs on day 4 of 2008 (day when the first sunspot with inverted magnetic field polarity after the prolonged solar minimum was observed). Since the time coverage (total number of points) is not the same in each time interval, we have normalized the number of hours spent in each specific bin to the total number of hours of each time interval. The dashed red lines in Figure 2a delimit the particle intensity frequency distribution in solar cycle 23 and are only plotted to guide the eye. The same dashed red lines are reproduced in Figure 2b to show that the periods with elevated particle intensities (i.e., above ~1 (cm$^2$ s sr MeV)$^{-1}$) were less frequent in solar cycle 24. Similarly, we have applied the same technique for the $P_{EP}$ data points in Figure 1b. The frequency distributions of $P_{EP}$ for solar cycles 23 and 24 are shown in Figures 2c and 2d, respectively. Correspondingly, solar cycle 24 showed a clear deficit of periods with elevated $P_{EP}$ at the higher pressures (i.e. $P_{EP}>10^3$ nPa).

We have repeated the same technique with the values of $P_B$ and $P_{PLS}$ displayed in Figures 1c and 1d. Figure 3 shows the resulting frequency distributions. The values $m$ and $\sigma$ in each panel indicate the mean and standard deviation of the $\log_{10}(P_B)$ and $\log_{10}(P_{PLS})$ distributions shown in Figures 1c-d, whereas the dashed red lines are only plotted to guide the eye. As found in prior studies [e.g., 1, 9] solar cycle 24 exhibited lower average values of $P_B$ and $P_{PLS}$ as displayed by the leftward shifted distributions in the bottom panels of Figure 3. In other words, mean elevated values of $P_B$ and $P_{PLS}$
were more frequent in solar cycle 23 than in solar cycle 24.

Finally, Figure 4 shows the frequency distributions of the ratios $P_{EP}/P_B$ (left) and $P_{EP}/P_{PLS}$ (right) computed from the data points shown in Figures 1e and 1f for solar cycles 23 (top) and 24 (bottom). The vertical dashed lines indicate the values $P_{EP}/P_B=1$ and $P_{EP}/P_{PLS}=1$, whereas the filled bars of the histograms indicate the occurrence of periods with $P_{EP}>P_B$ and $P_{EP}>P_{PLS}$. Clearly, periods with $P_{EP}>P_B$ and $P_{EP}>P_{PLS}$ were more frequent in solar cycle 23 than in solar cycle 24. Over the whole time interval considered in Figure 4, the probability of having $P_{EP}>P_B$ was 0.284% in solar cycle 23 in contrast to 0.155% in solar cycle 24, whereas for $P_{EP}>P_{PLS}$ the percentage was 0.845% in solar cycle 23 and 0.327% in solar cycle 24. Of course, these percentages may seem negligible when considering the whole duration of a solar cycle, but when considering only those time intervals associated with strong shocks the percentage occurrence of periods with $P_{EP}>P_B$ and $P_{EP}>P_{PLS}$ is not negligible.

3. Shock parameter statistics

Since most of the periods with $P_{EP}>P_B$ and $P_{EP}>P_{PLS}$ are usually observed in the upstream region of IP shocks [7, 8] we proceed here to analyze the properties of the shocks observed at 1 AU. There exist several catalogs of shocks observed at 1 AU (e.g., ipshocks.fi; www.cfa.harvard.edu/shocks; www.ssg.sr.unh.edu/mag/ACElists/obs_list.html) that use diverse methods to first select the shocks and then compute the shock parameters. Selection criteria and the lack of plasma measurements for the most intense events (i.e., IP shocks accompanied by high energetic particle intensities that usually saturate plasma instruments) are limiting factors that prevent us from having a complete and exhaustive list of shocks throughout the solar cycles.
Another limiting factor when using the shock catalogs is the accuracy of the shock parameters for the most intense events since none of the methods used to compute the shock parameters includes the pressure exerted by the energetic particles when solving the Rankine-Hugoniot conservation equations. The contribution of $P_{EP}$ in the momentum and energy conservation equations may not be negligible when $P_{EP}$ is of the same order or even exceeds $P_B$ and $P_{PLS}$. Therefore, the statistical study presented in this section is just provided for completeness of the possible differences between the two solar cycles, but it does not allow us to draw firm conclusions of the differences in the shock parameters for those events where $P_{EP} > P_B$ and $P_{EP} > P_{PLS}$.

Here we use the list of fast forward shocks observed by the Wind spacecraft cataloged in the heliospheric shock database maintained at the University of Helsinki by Kilpua et al. at ipshocks.fi [13]. At the time of writing this report, the Wind data set was the most complete of all the different data sets considered in the catalog, covering from 15 Nov 1994 up to 19 July 2016 (day of year 201). Although not coming from the same spacecraft as the energetic particle data, the Wind data set do enable us to compare on a statistical basis the shock properties between the two solar cycles (comparison of the shock parameters with the particle intensities on an event by event basis is beyond the scope of this article).

Figures 5a and 5b show the density compression ratio $r_n$ of the fast forward shocks observed by the Wind spacecraft as listed in ipshocks.fi. From day 242 of 1997 to day 4 of 2008 (Fig. 5a) a total of 301 fast forward shocks were analyzed in ipshocks.fi, whereas form day 4 of 2008 to day 201 of 2016 (Fig 5b) only 181 fast forward shocks were analyzed in ipshocks.fi. The distribution of shock compression ratios $r_n$ during both solar cycles had similar average and median values. Similarly, Figures 5c and 5d show the distribution of magnetosonic Mach numbers $M_s$ for the fast forward shocks cataloged in ipshocks.fi observed by the Wind spacecraft during solar cycles (a and c) 23 and (b and d) 24.
as magnetic compression ratio \( r_b \), shock speed \( V_s \), and the angle between the upstream magnetic field and the shock normal \( \theta_{Bn} \) (not shown here) did not show significant differences between solar cycles 23 and 24. Therefore, on average, the distributions of the shock parameters for the shocks reported in ipshocks.fi do not differ substantially between the two solar cycles.

The distributions of the properties of coronal mass ejections (CMEs) observed by coronagraphs in the two solar cycles shows considerable differences between one solar cycle and the next [e.g., 14, 15]. CMEs in solar cycle 24 were on average significantly slower, less massive and with a lower kinetic energy than in solar cycle 23 [15]. Figure 6a shows the annual number of CMEs from 1996 to 2015 observed by the Large Angle and Spectrometric Coronagraph (LASCO) on board the Solar and Heliospheric Observatory (SOHO) [16] with plane-of-sky speeds above 600 km s\(^{-1}\), angular widths larger than 20\(^\circ\), and positive computed masses as reported in the CME catalog of the Coordinated Data Analysis Workshop (CDAW) posted on cdaw.gsfc.nasa.gov/CME_list/ [17]. Figure 6b shows the annual number of X-ray flares observed by the Geostationary Operational Environmental Satellites (GOES) of class X or M as reported in the Daily Solar Data (DSD) files available at ftp.swpc.noaa.gov/pub/warehouse/. Statistical correlation studies between flares and CMEs over the two solar cycles can be found in [18]. Apart from the dependence with the solar activity (faster CMEs are more frequent during solar maximum), the number of fast CMEs in solar cycle 24 was lower than in solar cycle 23. On the other hand, CMEs in solar cycle 24 showed larger angular widths than in solar cycle 23 [14]. The drop in solar wind density, magnetic field, Alfvén speed, and of the sum of magnetic plus thermal pressure have been invoked as the main factors responsible for the larger expansion of the CMEs in solar cycle 24 [14]. The medium where CMEs propagate has also important effects in the strength of the shocks driven by these CMEs. In particular, since the magnetosonic speed of the solar wind showed also a decline in solar cycle 24 (cf. Figure 2 in [13]), the slower CMEs in solar cycle 24 were able to drive shocks with strengths comparable to those in cycle 23. In addition, the faster CMEs of solar cycle 23 propagated in a denser medium, resulting in shocks that weakened faster with helioradius than those in solar cycle 24. The likely result is that the shocks observed at L1 in both solar cycles displayed, on average, similar compression ratios and magnetosonic Mach numbers (cf. Fig. 5 and [13]).

The computation of the shock parameters requires determining the upstream region of the shocks. The catalog ipshocks.fi provides also the plasma parameters of the upstream region used to compute the shock parameters. Figure 7 shows the upstream plasma parameters that showed the largest differences between both solar cycles. In particular, Figures 7a and 7b show the distribution of the upstream magnetic field \( B_{up} \) and Figures 7c and 7d the distribution of the logarithm of the upstream solar wind proton temperature \( \log_{10}(T_{up}) \) for the fast forward shocks in solar cycle 23 (top panels) and solar cycle 24 (bottom panels) reported in ipshocks.fi. There is a larger tail of events with large values of \( B_{up} \) in solar cycle 23 yielding a larger average value of \( B_{up} \) in solar cycle 23 than in solar cycle 24. Similarly, Figures 7c and 7d show a slight trend for higher \( T_{up} \) values in solar cycle 24. The decrease of \( B_{up} \) and \( T_{up} \) in solar cycle 24 is a pure consequence of the general drop observed in magnetic field and solar wind parameters that constitute the medium where these shocks propagated [e.g., 1, 9].
4. Discussion

Periods when \( P_{EP} \) exceeds \( P_{B} \) and \( P_{PLS} \) are not infrequent (Fig. 1). When comparing solar cycles 23 and 24, we see that solar cycle 23 showed a larger number of time intervals dominated by \( P_{EP} \) than solar cycle 24 (Fig. 4). Although solar cycle 24 displayed a decrease of \( P_{B} \) and \( P_{PLS} \) (Fig. 3), the lower energetic particle intensities during this solar cycle (Fig. 2) translated into fewer periods where \( P_{EP} > P_{B} \) and \( P_{EP} > P_{PLS} \).

The general decrease in particle intensities observed in solar cycle 24 (Fig. 2) may be caused partly by the fewer fast CMEs occurring in this solar cycle (Fig. 6a), and partly by the fact that the interplanetary magnetic field magnitude was weaker than in solar cycle 23. Slower CMEs are in principle less efficient in driving strong shocks able to accelerate particles. However, the medium where these CMEs propagate is the dominant factor determining the formation and strength of a shock, and the distributions of shock parameters at 1 AU did not show clear differences between solar cycles 23 and 24 (Fig. 5). It has been argued that a weaker magnetic field causes the mechanisms of particle acceleration by shocks to act more slowly; and during the time over which a shock moves from the Sun to 1 AU, the slower acceleration rate results in a lower intensity of high-energy particles [19].

On the other hand, the seed particle population available for acceleration by shocks may have also been reduced in solar cycle 24 [20]. The origin of this seed particle population may include the solar wind itself, particles continuously accelerated in IP space by compression regions in thermally isolated systems [21], by magnetic reconnection in interacting magnetic islands [22, 23] or by solar wind stream interaction regions [24], as well as particles that originated in prior discrete solar events [25]. The decrease in solar wind density in solar cycle 24 would imply a deficit of thermal population available for particle acceleration. The lower level of solar activity in solar cycle 24 would imply a deficit of thermal population available for particle acceleration. The lower level of solar activity in solar cycle 24 would imply a deficit of thermal population available for particle acceleration. 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On the other hand, if shocks at 1 AU have similar characteristics in both solar cycles, the lower particle intensities in solar cycle 24 would result from the different properties of the upstream medium where shocks propagate. These properties include (1) lower magnetic field \( B_{ups} \) that translates into a slower particle acceleration at shocks, (2) lower proton temperature \( T_{ups} \) that implies a less energetic tail of the thermal population available for acceleration, and (3) a meager population of suprathermal particles originated in fewer discrete solar events. That would translate into fewer periods with \( P_{EP} > P_{B} \) and \( P_{EP} > P_{PLS} \) in solar cycle 24 when compared to solar cycle 23.
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This paper uses data from the Heliospheric Shock Database, generated and maintained at the University of Helsinki. All data used can be downloaded from www.srl.caltech.edu/ACE/ASC/ and spdf.gsfc.nasa.gov/pub/data/omni/low_res_omni/. We acknowledge the use of the SOHO LASCO CME catalog generated and maintained at the CDAW Data Center by NASA and The Catholic University of America in cooperation with the Naval Research Laboratory. SOHO is a project of international cooperation between ESA and NASA. This work is supported by NASA-HGI grant NNX16AF73G.

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