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Major Solar Energetic Particle Events of Solar Cycles 22 and 23: Intensities Close to the Streaming Limit

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Abstract It has been argued that the highest intensities measured near 1 AU during large solar energetic particle events occur in association with the passage of interplanetary shocks driven by coronal mass ejections, whereas the intensities measured early in the events (known as the prompt component) are bounded by a maximum intensity plateau known as the streaming limit. A few events in Solar Cycle 23 showed prompt components with intensities above the previously determined streaming limit. One of the scenarios proposed to explain intensities that exceed this limit in these events invokes the existence of transient plasma structures beyond 1 AU able to confine and/or mirror energetic particles. We study whether other particle events with prompt-component intensities close to the previously determined streaming limit are similarly affected by the presence of interplanetary structures. Whereas such structures were observed in four out of the nine events studied here, we conclude that only the events on 22 October 1989, 29 October 2003, and 17 January 2005 show interplanetary structures that can have modified the transport conditions in a way similar to those events with prompt components exceeding the previously determined streaming limit. The other six events with prompt components close to the previously determined streaming limit were characterized by either a low level of pre-event solar activity and/or the absence of transient interplanetary structures able to modify the transport of energetic particles.

Keywords Solar energetic particle events · Coronal mass ejections · Interplanetary shocks

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1. Introduction

By analyzing the largest solar energetic particle (SEP) events observed by the series of (US) National Oceanic and Atmospheric Administration/*Geostationary Operational Environmental Satellite* (NOAA/GOES) spacecraft during Solar Cycle 22, Reames and Ng (1998) showed that the energetic particle intensities measured early in a SEP event are bounded by a maximum intensity plateau known as the "streaming limit." These authors determined observationally the value of this streaming-limit intensity at different energy levels. They proposed a self-regulatory mechanism by which SEPs streaming along interplanetary magnetic field (IMF) lines amplify ambient magnetohydrodynamic (MHD) waves that in turn scatter the energetic particles, and hence restrict their streaming. Therefore, particle intensities measured early in a large SEP event (known as the prompt component of the SEP event) are bounded by a certain upper limit. According to these authors, the streaming limit can only be exceeded when the source of particles, in this case the interplanetary traveling shock driven by the parent coronal mass ejection (CME), reaches the spacecraft. Thus, the streaming limit (SL) applies only to the intensity of particles streaming from a distant source, *i.e.*, when the CME-driven shock is still close to the Sun, and not to those particles either accelerated locally when the shock arrives at 1 AU (known as the energetic storm particle (ESP) component) or partially trapped within and convected by solar-wind structures able to confine the energetic particles.

Lario, Aran, and Decker (2008) studied the major SEP events observed by the series of NOAA/GOES spacecraft during Solar Cycles 22 and 23 and found three (one) events in which the 40 – 80 MeV (165 – 500 MeV) proton intensities measured during the prompt component of the SEP events exceeded by a factor of four or more the previously determined SL. These events were observed during periods of intense levels of solar activity when multiple transient interplanetary (IP) structures, such as the interplanetary counterparts of CMEs (ICMEs), were present in the interplanetary medium. The MHD waves predicted to be amplified by SEPs far from the CME were not observed to accompany the promptly arriving particle component of the SEP events (even using observations from the two *Helios* spacecraft at heliocentric distances ranging from 0.3 to 0.98 AU; Alexander and Valdés-Galicia, 1998). Nonetheless, Lario, Aran, and Decker (2008; and references therein) suggested plausible mechanisms by which, in the context of the scenario proposed by Reames and Ng (1998), particle intensities in the prompt component of the SEP events may exceed the previously determined SL. These mechanisms include, apart from an intense source of particles, the inhibition of wave amplification by the streaming particles and/or the existence of large-scale IP structures able to modify the nominal conditions for SEP transport.

Figure 1 shows energetic-particle, solar-wind, and magnetic-field data for the four events found by Lario, Aran, and Decker (2008) having prompt component intensities in either the 40 – 80 MeV (P5) or the 165 – 500 MeV (P7) proton channels above the previously determined SL by a factor of four or more. From top to bottom each panel shows: (a) the corrected 40 – 80 and 165 – 500 MeV proton intensities measured by GOES and available at spidr.ngdc.noaa.gov, (b) the solar-wind speed measured by the *Solar Wind Electron, Proton, and Alpha Monitor* (SWEPAM) instrument onboard the *Advanced Composition Explorer* (ACE) and available at www.srl.caltech.edu/ACE/ASC/, (c) the magnetic field magnitude measured by the magnetometer onboard ACE and available at www.srl.caltech.edu/ACE/ASC/, (d) the number of CMEs per day (black thin line or white histogram) and the number of fast (>600 km s^{-1}) and wide ($>120°$) CMEs per day (black histogram) observed by the *Large Angle and Spectrometric Coronagraph* (LASCO) onboard the *Solar and Heliospheric Observatory* (SOHO) and reported at

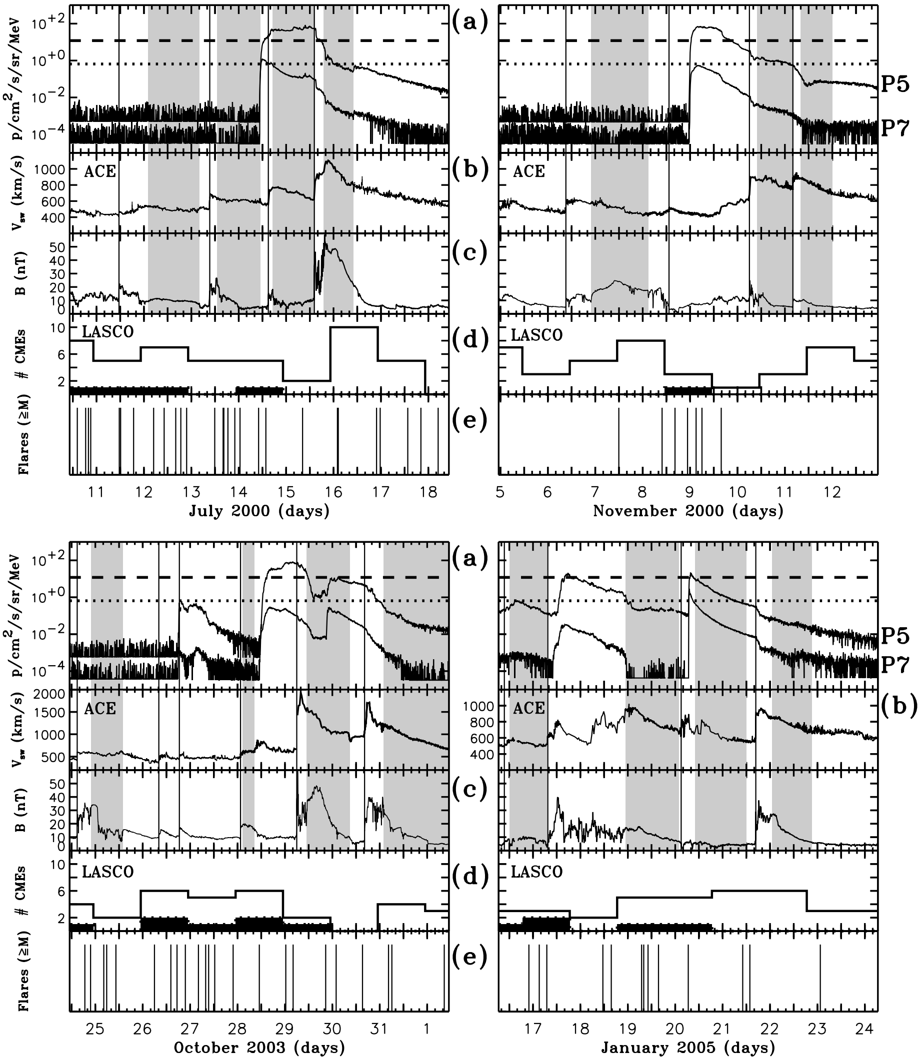

Figure 1 SEP events with prompt components exceeding the previously determined streaming limit by a factor of four or more. Clockwise: the 14 July 2000, 8 November 2000, 20 January 2005, and 28 October 2003 events. (a) Five-minute averages of the proton intensities measured at the energy channel P5 (top trace) and P7 (bottom trace). The horizontal dashed and dotted lines indicate the previously determined streaming limits by Reames and Ng (1998) in the channels P5 and P7, respectively. (b) Solar-wind speed. (c) Magnetic-field magnitude. (d) Daily number of CMEs (solid line) and fast (>600 km s^{-1}) and wide (>120°) CMEs (black histogram) as observed by LASCO. (e) Occurrence of X-ray flares above C-class (thin vertical lines). The vertical solid lines and gray vertical bars in panels (a – c) indicate the passage of interplanetary shocks and ICMEs, respectively.

cdaw.gsfc.nasa.gov/CME_list/, and (e) the occurrence of X-ray flares of class M or X (vertical thin lines) as reported by *Solar Geophysical Data.* The vertical solid lines and the gray vertical bars in Figures 1(a), (b), and (c) indicate the passage of interplanetary shocks and ICMEs as identified by Lario, Aran, and Decker (2008). The two horizontal dashed and dotted lines in Figure 1(a) indicate the previously determined SL as identified by Reames and

Table 1 Events with prompt components above the previously determined streaming limit by a factor of four or more

Event	Solar Flare
14 July 2000	X5/3B N22W07
8 November 2000	M7/3F N10W77
28 October 2003	X17/4B S16E08
20 January 2005	X7/2B N12W61

Ng (1998). Each panel in Figure 1 covers four days prior to and after the onset of the SEP event. Whereas the prompt components of the SEP events on 14 July 2000, 8 November 2000, and 28 October 2003 exceeded by a factor of four or more the previously determined SL in the energy channel 40 – 80 MeV (P5), only the 20 January 2005 SEP event exceeded the limit by a factor of four or more in the energy channel 165 – 500 MeV (P7), and did so for only a period of $\approx$ two hours. Table 1 lists the solar events associated with the origin of these four SEP events.

The scenarios suggested by Lario, Aran, and Decker (2008) to explain, in the context of the ideas advanced by Reames and Ng (1998), why the previously determined SL was exceeded during these four SEP events invoke the existence of large-scale IP structures able to modify the nominal conditions for SEP transport. As noted above, all four events occurred during periods of intense levels of solar activity when multiple solar flares and CMEs occurred at the Sun (Figures 1(d) and (e)) and multiple transient ICMEs were present in interplanetary space (gray bars in Figure 1). Large-scale plasma structures were observed at 1 AU just prior to the onset of the four SEP events. The presence of these plasma structures beyond 1 AU at the time of the SEP injection may have been responsible for the enhancement of particle intensities observed at 1 AU above the previously determined SL. Plasma structures beyond the spacecraft location may act as magnetic barriers able to increase the fraction of energetic particles reflected and/or scattered back to 1 AU, and thus, contribute to the enhancement of the observed particle intensities (Lario, Decker, and Aran, 2008). That was the case for all the SEP events shown in Figure 1 (see Lario, Aran, and Decker, 2008, and references therein).

A pertinent question to ask is whether these plasma structures were also present at the time of the SEP events whose prompt component intensities remained below or close to the SL. An analysis of all solar-wind structures observed during all of the SEP events with particle intensities below the previously determined SL is not possible to accomplish within a reasonable research effort. In this article we analyze those SEP events measured by the GOES spacecraft in Solar Cycles 22 and 23 whose hourly averaged 40 – 80 MeV and/or 165 – 500 MeV proton intensities measured during their prompt components reached values above the previously determined SL multiplied by a factor of 0.9 (but did not exceed the previously determined SL by a factor of four). Hereafter, we use this definition to identify those events with prompt components close to the streaming limit (*i.e.*, $0.9 \times \mathrm{SL} <$ maximum intensity in the prompt component $< 4 \times \mathrm{SL}$). We discuss whether the scenarios proposed by Lario, Aran, and Decker (2008) to explain prompt SEP intensities exceeding the previously determined SL occurred during these less intense events.

2. SEP Events with Prompt Components Close to the Previously Determined Streaming Limit

Among the SEP events with prompt components close to the previously determined SL, we distinguish those events that showed an intense ESP component (with intensities in the channel P5 above 4 × SL) from those events without a strong ESP component. The observation of a strong ESP component depends not only on the location of the observer with respect to the traveling CME-driven shock (as seen from the Earth, SEP events with strong ESP components are usually generated close to the Central Meridian), but also on the capability of the shock to either accelerate or confine energetic particles in its vicinity when it arrives at 1 AU (Lario and Decker, 2002).

Table 2 lists the solar events associated with the origin of the SEP events with prompt components close to (as per our definition) the previously determined SL and analyzed in this section. We distinguish those events with ESP component above 4 × SL in the P5 channel (19 October 1989 and 4 November 2001) from those without an intense ESP component. Note that the events on 14 July 2000 and 28 October 2003 (Figure 1) are also associated with the arrival of strong shocks showing intense ESP components (at least in the P5 energy channel); however, these ESP components did not stand out in the time-intensity profiles because the SL was already exceeded during their prompt components.

The third column of Table 2 indicates whether IP structures capable of reflecting energetic particles from beyond the spacecraft, and thus, modifying the nominal particle transport (as suggested by Lario, Aran, and Decker, 2008, to explain the exceeding of the SL for the events shown in Figure 1) can be inferred in each one of the events. Single-point measurements allow us to infer only a general picture of the large-scale structure of the interplanetary medium surrounding the observer. However, uncertainties about *i*) the evolution of the transient IP structures as they move beyond the spacecraft, *ii*) the magnetic connection established between these IP structures and the spacecraft, and *iii*) the ability of these structures to reflect energetic particles back to 1 AU are inherent in our study based only on single-point observations. In Sections 2.1 and 2.2 we discuss the rationale used to determine the existence of IP structures able to modify the energetic particle transport in each event (Yes/No in the third column of Table 2). We also discuss whether the observation of the events with a prompt component close to the SL (as per our definition) is consistent with the scenario proposed by Lario, Aran, and Decker (2008) in which IP structures beyond the spacecraft were able to reflect energetic particles back to the observer, and thus, increase particle intensities above the SL (fourth column in Table 2).

Since all of the events listed in Table 2 have prompt components below (or close to) the previously determined SL, they all agree with the scenario proposed by Reames and Ng (1998), where, in principle, the first injected particles amplify MHD waves that restrict the streaming of the subsequent injected SEPs (although these waves have not been observed far from CME-driven shocks; *e.g.*, Alexander and Valdés-Galicia, 1998). In order to amplify ambient MHD waves, however, it is necessary that the first injected particles propagate in a medium where MHD turbulence is already present. As described in Section 2.2, we found two events in which the first SEPs propagated within ICMEs where, in general, magnetic field fluctuations are low and MHD waves are scarce. Therefore, it is unlikely that the first injected SEPs in these events generated enough MHD waves to maintain particle intensities below the SL. This is in contradiction to the scenario suggested by Reames and Ng (1998). We indicate in the last column of Table 2 whether the events studied in Sections 2.1 and 2.2 are consistent with the scenario proposed by Reames and Ng (1998).

It is worth mentioning that, in general, the observation of an intense SEP event with a prompt component close to or exceeding the previously determined SL not only depends on the existence of an intense source of particles (either close to the Sun or traveling through the interplanetary medium), but also on the location of the observer with respect to the source of particles. The existence of transient plasma structures able to confine or mirror energetic particles (Lario, Decker, and Aran, 2008) complicates the picture since the observation of

Table 2 Events with prompt components close to the streaming limit

Events with intense ESP components				
Event	Solar Flare	Pre-event IP structures beyond 1 AU	Consistency with the Lario, Aran, and Decker (2008) scenario	Consistency with the Reames and Ng (1998) scenario
19 October 1989	X13/4B S27E10	No	Yes	Yes[a]
4 November 2001	X1/3B N06W18	No[b]	Yes	Yes[a]
Events without intense ESP components				
Event	Solar Flare	Pre-event IP structures beyond 1 AU	Consistency with the Lario, Aran, and Decker (2008) scenario	Consistency with the Reames and Ng (1998) scenario
12 August 1989	X2/2B S16W37	No	Yes	Yes
29 September 1989	X9/- ≈S26W105	No	Yes	Yes
22 October 1989	X2/2B S27W31	Yes	No	No[c]
15 April 2001	X14/2B S20W85	Yes	Yes[d]	Yes[d]
22 November 2001	M3/2B S25W67 M9/2N S15W34	No[b]	Yes	Yes
29 October 2003	X10/2B S15W02	Yes	No	No[c]
17 January 2005	X3/2F N13W23	Yes	No	Yes

[a] Transient structures around or in front of the CME-driven shock contributed to both form an intense ESP component at the arrival of the shock at 1 AU and reduce the prompt component of the SEP event.

[b] Presence of an ICME beyond the observer at the time of the onset of the SEP event that presumably did not produce large solar-wind and magnetic-field enhancements able to reflect energetic particles back to 1 AU.

[c] First injected SEPs propagated within an ICME where there is a deficit of MHD waves to amplify, contrary to the scenario proposed by Reames and Ng (1998).

[d] Diffusive transport inferred from the analysis of neutron-monitor observations favors the amplification of MHD waves (consistent with Reames and Ng, 1998) and reduces the role of IP structures beyond 1 AU. Additionally, the presence of intervening structures implies a diminished role of the IP structures beyond 1 AU.

these confined or reflected particles depends on both the location of the observer with respect to these structures and how the spacecraft establishes magnetic connection to these structures. Therefore, it is possible that an event observed near Earth and classified as a major SEP event (such as the events listed in Tables 1 and 2) will be classified as moderate or weak from another heliospheric location (if observed at all). We will assume for the analysis of the events selected in this article that such an intense source of particles close to the Sun exists.

2.1. Events with Intense ESP Components

Figure 2 shows, in the same format as Figure 1, the SEP events with onsets on 4 November 2001 and 19 October 1989. Solar-wind and magnetic-field data for the 4 November 2001 event were measured by instruments on ACE. During the October 1989 event, *Interplanetary Monitoring Platform-8* (*IMP-8*) was the only near-Earth monitor of the solar wind. Owing to the limited solar-wind data from IMP-8 (either because of data gaps or

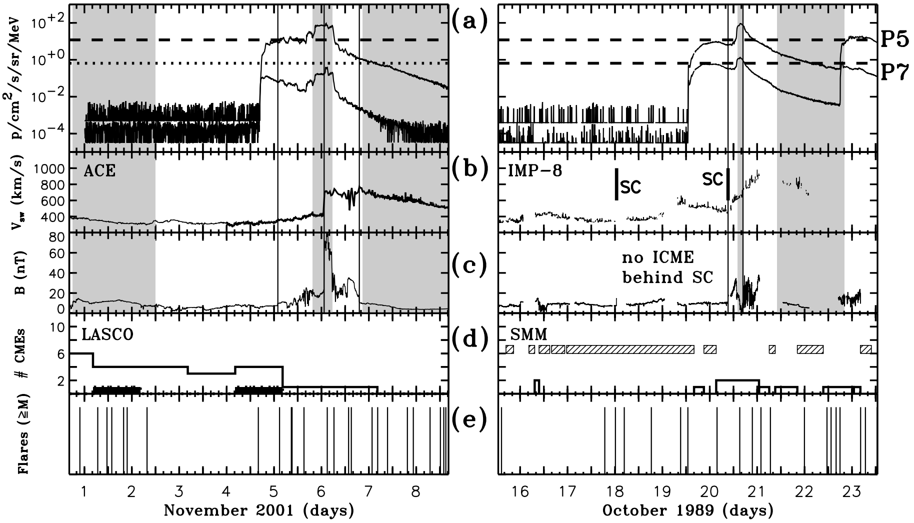

Figure 2 The SEP events on 4 November 2001 (left), and 19 October 1989 (right) with prompt components close to the previously determined streaming limit but ESP components exceeding the previously determined streaming limit by a factor of four or more. From top to bottom (a) Five-minute averages of the proton intensities measured at the energy channel P5 (top trace) and P7 (bottom trace). The horizontal dashed and dotted lines indicate the previously determined streaming limits by Reames and Ng (1998) in the channels P5 and P7, respectively. (b) Solar-wind speed. (c) Magnetic-field magnitude. (d) Daily number of CMEs (solid line) as observed by LASCO (left) and by SMM (right). The black histogram on the left shows the daily number of fast (>600 km s^{-1}) and wide (>120°) CMEs, whereas the hatched bars on the right show the data gaps of the SMM coronagraph. (e) Occurrence of X-ray flares above C-class (thin vertical lines). The vertical solid lines and gray vertical bars in panels (a – c) indicate the passage of interplanetary shocks and ICMEs, respectively.

IMP-8's traversal of Earth's magnetotail), the passage of IP shocks and/or ICMEs at 1 AU can go undetected. For that reason we add, in the right graph of Figure 2(b), the occurrence of sudden storm commencements (indicated by SC) as reported in *Solar Geophysical Data*. Fortunately, Cane and Richardson (1995) analyzed solar-wind data during the October 1989 period. The identification of ICMEs and IP shocks in the right part of Figure 2 follows that work. Based on the anisotropy information inferred from polar neutron monitors, Ruffolo *et al.* (2006) proposed that the ICME beginning on 21 October 1989 extended until the onset of the SEP event at the end of 22 October 1989. The identification of shocks and ICMEs during the period of 1 – 8 November 2001 (left-part of Figure 2) follows the list of near-Earth ICMEs (1996 – 2007) compiled by Richardson and Cane at www.ssg.sr.unh.edu/mag/ace/ACElists/ICMEtable.html.

Figure 2(d) shows the number of CMEs per day observed by LASCO and reported on cdaw.gsfc.nasa.gov/CME_list/ (left) and by the coronagraph onboard the *Solar Maximum Mission* (SMM) and reported on mlso.hao.ucar.edu/smm/ (right). Note that *i*) the restricted field-of-view (just one quadrant from 1.6 to ≈6 solar radii), *ii*) the sensitivity, and *iii*) the numerous data gaps (indicated by hatched horizontal bars in the right graph of Figure 2(d)) of the SMM coronagraph (Vourlidas *et al.*, 2003) led, in general, to a smaller number of CMEs per day observed by SMM than that observed by LASCO (white histograms in Figure 2(d)). When a SMM data gap is present on the day that we recount the number of CMEs, the width of the bar in the histogram of the right graph of Figure 2(d) extends only from the end of the previous data gap to the beginning of the next data gap (if it spans less than one day).

Because of the different field-of-view of the SMM coronagraph, the widths and speeds of the CMEs reported on mlso.hao.ucar.edu/smm/ differ from the widths and speeds estimated from LASCO images. Therefore, we indicate in the right graph of Figure 2(d) only the number of CMEs per day and not the number of wide ($>120^\circ$) and fast ($>600\ \mathrm{km\,s^{-1}}$) CMEs per day as we do for those cases when LASCO observations are available (*e.g.*, solid black histogram in the left graph of Figure 2(d)).

Comparing the events shown in Figures 1 and 2 we see that, prior to the onset of the two SEP events shown in Figure 2, the number of flares was relatively low and no ICMEs were observed in the proximity of Earth. At the time of the onset of the SEP event on 4 November 2001, the leading (trailing) edge of the ICME observed at 1 AU between 1 – 2 November was at $\approx$0.83 ($\approx$0.45 AU) beyond the orbit of Earth, assuming that it propagated at the solar wind speed observed at 1 AU when the leading (trailing) edge crossed this distance. This ICME was not as fast and strong as the ICMEs observed prior to the onset of the SEP events shown in Figure 1, and presumably it was unable to produce strong field compressions beyond 1 AU.

The SEP events in Figure 2 show that particle intensities above $4 \times$ SL were observed only in association with the passage of two IP shocks, *i.e.*, during the ESP components. Both ESP intensity enhancements were observed even in the energy channel 160 – 500 MeV, and both were characterized by the presence of a transient structure indicated by the thin vertical gray bars in Figure 2 and initially classified as an ICME (Cane and Richardson, 1995; Shen *et al.*, 2008). Lario and Decker (2002) showed that the ESP on 20 October 1989 was not due to local acceleration of particles by the CME-driven shock, but rather to the transient structure that formed in front of the CME-driven shock and was able to confine energetic particles. Similarly, Shen *et al.* (2008) showed that the ESP event on 6 November 2001 was also shaped by the structure of the ICME within which the CME-driven shock associated with the main SEP event propagated. Both structures were able to confine energetic particles around the CME-driven shock. We conclude that *i*) the absence of remote transient IP structures beyond 1 AU at the onset of the SEP event, and *ii*) the presence of local transient structures at or within 1 AU that confined particles around the CME-driven shock both contributed to maintain the prompt component of the SEP events below the previously determined SL.

2.2. Events without Intense ESP Components

Figures 3 and 4 show, in the same format as Figure 1, those events of Solar Cycles 22 and 23 with 40 – 80 MeV and/or 165 – 500 MeV proton prompt-component intensities close to (as per our definition) the previously determined SL, but without intense ESP components. The bottom-left panel of Figure 1 includes the SEP event on 29 October 2003 that also met our selection criterion (see Table 2). Magnetic-field and solar-wind data shown in Figures 3 and 4 were collected by IMP-8 (for those events observed in 1989) and by ACE (for those events in 2001 and 2005). The location of IMP-8 within the magnetosphere, and hence, the data gaps in the solar wind data are indicated in the respective panels. Similarly, we use the LASCO catalog to determine the number of CMEs per day during the SEP events in 2001 and 2005, and the SMM catalog for those SEP events in 1989, as indicated in Figures 3(d) and 4(d).

In comparison to the events shown in Figure 1, all of the events shown in Figure 3 were characterized by low levels of pre-event solar activity (as indicated by the occurrence of class-M-and-above X-ray flares in Figure 3(e)). Pre-event particle intensities before the onset of the events shown in Figure 3 were at background level. The two events in 1989 were characterized by the absence of large-scale solar-wind structures beyond 1 AU at the time of

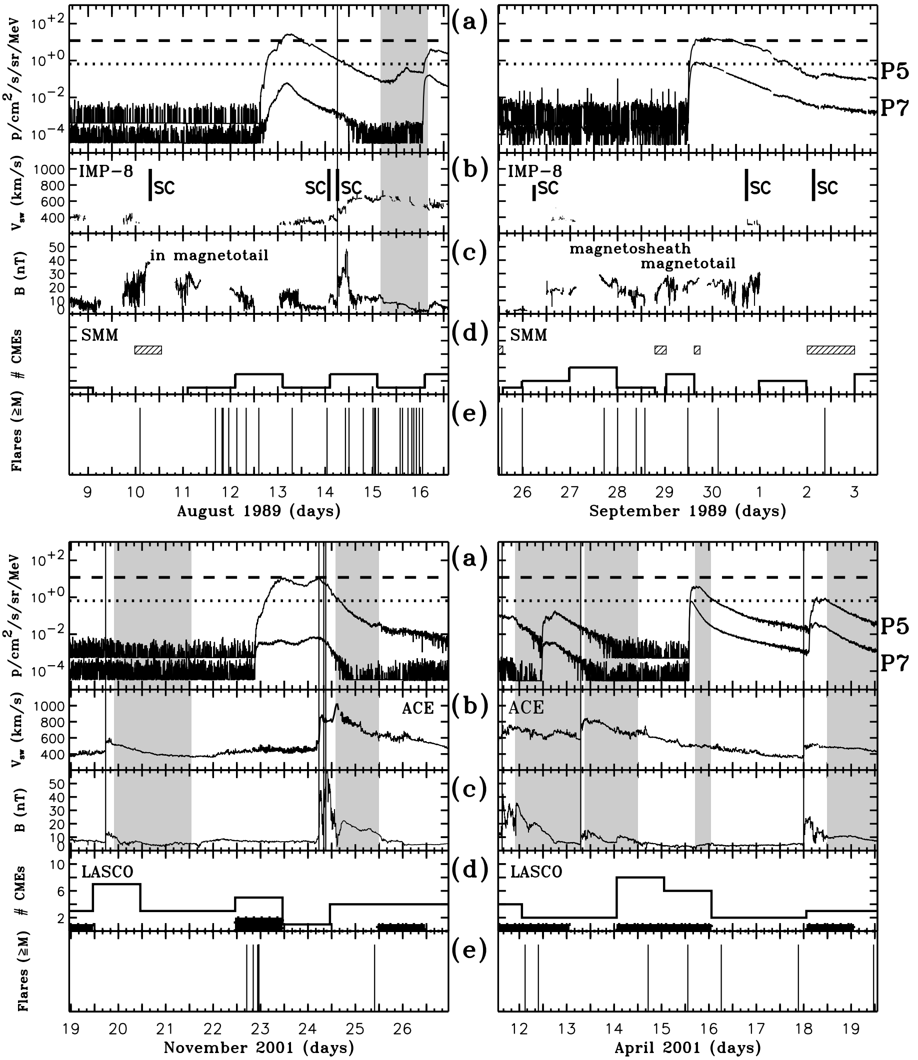

Figure 3 The SEP events on 12 August 1989 (top left), 29 September 1989 (top right), 22 November 2001 (bottom left), and 15 April 2001 (bottom right) with prompt components close to the previously determined streaming limit. The format of this figure is identical to that of Figures 1 and 2.

the onset of the SEP event. The event on 12 August 1989 constituted the first in a series of events occurring in mid-August, prior to which time the interplanetary medium was devoid of transient plasma structures (Richardson, Farrugia, and Winterhalter, 1994). Prior to the event on 29 September 1989, the level of activity was also very low (Swinson and Shea, 1990).

Regarding the origin of the SEP event on 22 November 2001, it is worth noting that a first halo CME was observed by LASCO at 20:30 UT on 22 November 2001 with a plane-of-sky speed of 1443 km s^{-1} and temporally associated with a M3/2B flare at S25W67. A first SEP intensity enhancement was observed in the energy channels P5 and P7 in response to this

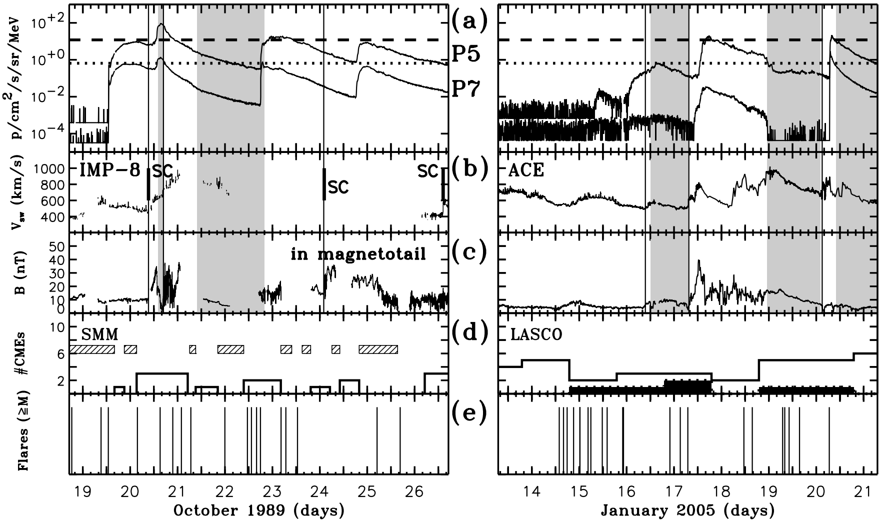

Figure 4 The SEP events on 22 October 1989 (left), and 17 January 2005 (right) with prompt components close to the previously determined streaming limit. The format of this figure is identical to that of Figure 2.

solar event. LASCO observed a second halo CME at 23:30 UT with a speed of 1437 km s^{-1} temporally associated with a M9/2N flare at S15W34 producing a new increase in GOES particle intensities. If the first halo CME (at ≈0.1 AU from the Sun at the time of the second halo CME assuming that it propagated at a constant speed of 1443 km s^{-1}) contributed to attenuate the particle intensities at 1 AU (as suggested in the case of intervening structures by Lario, Decker, and Aran, 2008) that would have contributed to maintaining intensities below the SL.

Regarding the situation beyond the observer at the time of the onset of the SEP event on 22 November 2001, we note that the only fast (>600 km s^{-1}) and wide (>120°) CME occurring prior to the onset of the event occurred on 18 November 2001 at 21:30 UT (a halo CME with an estimated plane-of-sky speed of 888 km s^{-1}) as reported on cdaw.gsfc.nasa.gov/CME_list/ that, at the time of the onset of the SEP event on 22 November 2001, would have been located at ≈0.5 AU beyond the orbit of Earth (assuming that it propagated at a constant speed of 888 km s^{-1}). Similarly, at the time of the onset of the SEP event, the ICME observed earlier at 1 AU on 20–21 November 2001 extended from 0.91 AU to 0.30 AU beyond the orbit of Earth (assuming that the ICME propagated at the solar-wind speed observed at 1 AU when the leading and trailing edges crossed this distance). The transient structure formed in front of this ICME was not as fast as the ones formed in front of the ICMEs observed prior to the onset of the SEP events shown in Figure 1. Similarly, the magnetic field increase associated with this ICME was not as strong as that associated with the ICMEs observed prior to the onset of the SEP events shown in Figure 1. Presumably this ICME on 20–21 November 2001 was unable to produce strong field compressions beyond 1 AU. Therefore, we argue that the interplanetary medium prior to the occurrence of the SEP events on 12 August 1989, 29 September 1989, and 22 November 2001 was relatively free of transient IP structures able to modify the nominal conditions for the transport of SEPs.

Prior to the onset of the event on 15 April 2001, the occurrence of class-M-and-above X-ray solar flares was relatively low, but not the number of CMEs as observed by LASCO.

From 9 April 2001 to 12 April 2001 at least a fast ($>1100\ \mathrm{km\,s^{-1}}$) halo CME was observed daily. However, only one wide ($>120°$) and fast ($>600\ \mathrm{km\,s^{-1}}$) CME was observed throughout 13 and 14 April 2001 and until the onset of the event at midday 15 April 2001. This was a partial-halo CME at 21:30 UT on 14 April 2001 with plane-of-sky speed of 764 $\mathrm{km\,s^{-1}}$ that, at the time of the onset of the SEP event on 15 April 2001, was at ≈ 0.3 AU from the Sun (assuming that it propagated at a constant speed of 764 $\mathrm{km\,s^{-1}}$). Prior to this CME, another 113°-wide 830 $\mathrm{km\,s^{-1}}$ West-directed CME was observed at 17:54 UT on 14 April 2001. If these intervening structures acted as an attenuating factor for the particle intensities observed at 1 AU after the injection of SEPs on 15 April 2001 (as suggested in the case of intervening structures by Lario, Decker, and Aran, 2008) that would have helped to maintain particle intensities below the SL.

Two ICMEs were observed prior to the onset of the SEP event on 15 April 2001 with leading edges at 22:00 UT on 11 April 2001 and 09:00 UT on 13 April 2001 and trailing edges at 07:00 UT on 13 April 2001 and 12:00 UT on 14 April 2001, respectively. At the time of the onset of the event on 15 April 2001, the second ICME extended from 1.04 AU to 0.40 AU beyond the orbit of Earth (assuming that the ICME propagated at the solar wind speed observed at 1 AU when the leading and trailing edges crossed this distance; *i.e.*, 830 $\mathrm{km\,s^{-1}}$ and 680 $\mathrm{km\,s^{-1}}$, respectively). This fast ICME propagated behind the first slower ICME. The combination (and possible merging) of both ICMEs most probably produced a strong compression in the solar wind. Note that a high-density enhanced magnetic field structure was observed at 1 AU at the end of 11 April 2001 that, at the time of the onset of the SEP event, was at ≈ 1.44 AU beyond the orbit of Earth. Single-point observations at the particle energies considered here do not allow us to specify whether this distant magnetic field increase was able to reflect particles injected from the Sun on 15 April 2001.

The SEP event on 15 April 2001 only reached the previously determined SL in the P7 energy channel and 60 ± 5 minutes after the onset of the event, whereas P5 intensities remained below the previously determined SL at this energy. Bieber *et al.* (2004) analyzed neutron monitor observations during this event and suggested that the transport of ≈ 1 GeV protons was diffusive (with a radial mean free path of 0.17 AU). The transport simulation to simultaneously reproduce neutron-monitor intensities and anisotropies during this event did not include either the presence of intervening plasma structures or any magnetic bottleneck or reflecting boundary as done, for example, in the case of the 14 July 2000 event (Bieber *et al.*, 2002). Bombardieri *et al.* (2007) studied the relativistic proton intensities (from 120 MeV to 10 GeV) observed during the event on 15 April 2001 and concluded that the low anisotropy observed after the onset of the event was due to turbulence associated with the interplanetary magnetic field. Therefore, in the context of the scenario proposed by Reames and Ng (1998), and following the results of the transport simulation by Bieber *et al.* (2004) and Bombardieri *et al.* (2007), the SEP transport in this event was dominated by scattering processes in high levels of pre-existing magnetic fluctuations presumably from the intervening IP structures originated by prior CMEs. These processes limit the streaming of the particles, and hence, the intensities measured at 1 AU remained below or close to the SL, in agreement with the scenario suggested by Reames and Ng (1998), and also suggest that the role of the IP structures beyond 1 AU in modifying the nominal energetic particle transport was diminished.

The SEP events on 22 October 1989, 17 January 2005, and 29 October 2003 were part of a series of events generated by either a single active region in the case of October 1989 (Shea *et al.*, 1995) and January 2005 (Malandraki *et al.*, 2007) or in a combination of two active regions in the case of October 2003 (Lario *et al.*, 2005). Figure 4 shows, in the same format as Figure 1, data for the events on 22 October 1989 and 17 January 2005, whereas the event on 29 October 2003 is shown in the bottom-left graph of Figure 1. Similarly to previous figures, we use solar wind and magnetic field from IMP-8 and CME observations from SMM for those events in 1989, whereas solar wind and magnetic field data come from ACE and CME observations from LASCO for those events in 2003 and 2005.

Based on the limited solar-wind and magnetic-field data taken prior to the onset of the event on 22 October 1989, Cane and Richardson (1995) identified an ICME passage starting at ≈10:00 UT on 21 October 1989. Based on the bidirectional distribution of ≈1 – 3 GV protons measured by polar neutron-monitor stations at the onset of the SEP event on 22 October 1989, Ruffolo *et al.* (2006) suggested that this ICME extended well after ≈18:00 UT on 22 October 1989. We extended the gray bar in the panel of the 22 October 1989 SEP event in Figure 4 until the onset of the SEP event on that day (≈20:00 UT). Unfortunately, GOES particle data do not allow us to infer particle flow anisotropy information. Ruffolo *et al.* (2006) suggested that the first particles were injected onto both legs of a closed interplanetary magnetic loop rooted at the Sun and crossing the Earth at the time of the SEP injection. Later on, either particles escaping from the loop and/or particles continuously injected from close to the Sun constituted the decay phase of the SEP event. If this is the case, the transport of the first SEPs injected in this event occurred within an ICME. Both the lack of magnetic-field oscillations and the low plasma β parameter typically observed within ICMEs lead to the conclusion that energetic particles propagate within these structures with large mean free paths (Tranquille *et al.*, 1987; Torsti, Riihonen, and Kocharov, 2004), making the amplification of MHD waves by propagating SEPs difficult (Reames, Ng, and Berdichevsky, 2001). In fact, transport simulations by Ruffolo *et al.* (2006) to simultaneously fit neutron monitor intensity and anisotropy measurements in this event required a parallel mean free path of 1.2 – 2.0 AU along the closed magnetic field loop for ≈1 – 3 GV protons. However, particle intensities at the onset of the 22 October 1989 SEP event remained below the SL. In the context of the scenario proposed by Reames and Ng (1998), intensities below the SL result from the scattering processes between particles and waves amplified by the particles themselves. However the amplification of these waves would have been reduced in a low β plasma such as inside an ICME.

The onset of the event at the end of 29 October 2003 also occurred within an ICME, and similarly, the intensities remained below the SL (Figure 1). Details of both this SEP event and the IP structures observed in this period can be found in Lario *et al.* (2005) and (Malandraki *et al.*, 2005). Both events (22 October 1989 and 29 October 2003) conflict with the idea proposed by Reames and Ng (1998) that wave generation restricts the streaming of energetic particles (and hence intensities below the SL) because SEPs propagating within an ICME (*i.e.*, in a low β region) do not encounter ambient MHD waves to amplify (Reames, Ng, and Berdichevsky, 2001).

The remainder of the SEP events on 22 October 1989 and 29 October 2003 were constituted by energetic particles propagating outside the ICME and probably accelerated by the CME-driven shocks observed at 1 AU on 24 October 1989 and 30 October 2003, respectively. The transport of these SEPs was most probably modified not only by the presence of the pre-event ICME itself, but also by the previous shocks observed earlier on 20 October 1989 and 29 October 2003. Because of the single-point measurements at 1 AU, it is not possible to infer the complete structure of the interplanetary medium before the injection of SEPs on 22 October 1989 and 29 October 2003. However, the observation of all these structures prior to the onset of the event is one of the scenarios suggested by Lario, Aran, and Decker (2008) to explain the exceeding of the SL in the SEP events shown in Figure 1. If this is the case, the events on 22 October 1989 and 29 October 2003 depart from the scenarios proposed by Lario, Aran, and Decker (2008) to explain, in the context of the theory proposed by Reames and Ng (1998), the exceeding of the SL.

The onset of the SEP event on 17 January 2005 occurred just after the passage of an ICME. The rising phase of the event was affected by the passage of an enhanced magnetic field structure that may have produced a weakening of the intensity of particles prior to its passage, but an enhancement after its passage (if it was able to confine particles behind it) (Lario, Decker, and Aran, 2008). The level of solar activity during the days preceding the onset of the event on 17 January 2005 was characterized by the observation of at least one halo CME per day (from 13 January to the onset of the event). The presence of all of these structures in the interplanetary medium prior to the onset of the SEP event may result in a situation similar to the scenarios proposed by Lario, Aran, and Decker (2008) to explain, in the context of the theory proposed by Reames and Ng (1998), the exceeding of the previously determined SL. However, the intensity in this event remained below (or close to) the previously determined SL. Note also the low intensities reached in the P7 energy channel (similarly to the 12 August 1989 and 22 November 2001 events). Therefore, we conclude that in this event either the source of high-energy particles was not intense enough, or the existent structures beyond the observer were not able to affect the SEP transport, in contradiction with the scenarios proposed by Lario, Aran, and Decker (2008).

In summary, out of the nine events with prompt components close to (as per our definition) the previously determined SL that met our selection criterion, four (15 April 2001, 22 October 1989, 29 October 2003, and 17 January 2005) showed complex IP structures similar to the scenarios proposed by Lario, Aran, and Decker (2008) to explain the exceeding of the SL in the events shown in Figure 1. However, particle intensities remained below (or close to) the SL, evidently because either the particle sources were not intense enough to exceed the streaming limit or the IP structures did not modify the SEP transport, as suggested by Lario, Aran, and Decker (2008). According to the analysis of the neutron-monitor data during the 15 April 2001 event, the particle transport was very diffusive, and therefore, the role of the IP structures beyond 1 AU was diminished. The events on 15 April 2001, 22 November 2001, and 17 January 2005 showed the presence of intervening structures between the Sun and the observer capable of attenuating the particle intensities observed at 1 AU, and hence, contribute to maintain intensities below the SL (as suggested by Lario, Decker, and Aran, 2008). The events that are especially in conflict with the scenarios proposed by Reames and Ng (1998) are those on 22 October 1989 and 29 October 2003. During these events the first injected particles propagated within an ICME to reach 1 AU where, in principle, the presence of MHD waves to amplify is scarce.

Finally, we would like to emphasize that the scenarios proposed in Lario, Aran, and Decker (2008) and Lario, Decker, and Aran (2008) (and references therein) did not address important issues, such as the fact that self-amplified waves were not detected in association with the prompt component of SEP events (Alexander and Valdés-Galicia, 1998) or whether the Sun can even accelerate enough particles to exceed the streaming limit. Rather, the scenarios proposed only try to reconcile the theory developed by Reames and Ng (1998) with the observation of SEP events with prompt components above the previously determined SL.

3. Conclusions

Lario, Aran, and Decker (2008) proposed a series of scenarios to explain, in the context of the theory developed by Reames and Ng (1998), the exceeding by a factor of four or more of the previously determined SL observed during the prompt component of four major SEP events in Solar Cycle 23 (Figure 1). These scenarios invoke the existence of transient IP solar-wind structures beyond 1 AU able to confine and/or mirror energetic particles, and thus, enhance the particle intensities measured at 1 AU. We analyze whether such transient solar-wind structures existed during the SEP events of Solar Cycles 22 and 23 whose prompt intensities were close to the previously determined streaming limit (where “close to” means $0.9 \times \mathrm{SL} <$ maximum particle intensity measured in the prompt component $< 4 \times \mathrm{SL}$). We find two events in which particle intensities exceeded by a factor of four or more the SL, but did so only during their ESP components. In these two cases plasma structures formed in front of the associated CME-driven shock were able to confine the shock-accelerated particles, and thus, not only reduce the intensity of the prompt component of the SEP events, but also increase the intensities observed in association with the arrival of the CME-driven shock at the spacecraft.

Regarding the SEP events with prompt components close to the SL, but without intense ESP components, we find that, in contrast to the events with prompt components above the SL, the pre-event situation was characterized by a low level of solar activity, low energetic-particle intensities, and an interplanetary medium beyond 1 AU devoid of transient structures able to potentially reflect energetic particles. The exceptions were the event on 15 April 2001 where the SEP transport was essentially diffusive (and hence the possible existence of waves able to limit the streaming of energetic particles), and the events on 22 October 1989, 29 October 2003, and 17 January 2005, where previous events and ICMEs complicated the scenario. The first particles injected in the 22 October 1989 and 29 October 2003 events propagated within a prior ICME where, in principle, there is a low level of ambient MHD fluctuations, and hence an increased difficulty for SEPs to amplify MHD waves. These observations contradict the scenario proposed by Reames and Ng (1998) because, in order to maintain particle intensities below the SL, it is necessary to generate enough waves to restrict the particle streaming. The 17 January 2005 event occurred when multiple transient structures were present in the interplanetary medium, which contradicts the scenario proposed by Lario, Aran, and Decker (2008) to explain, in the context of the Reames and Ng (1998) theory, the exceeding of the SL. Either the seed particle sources were not intense enough to produce particle intensities above the SL, or the transient structures did not have an effect of confining and mirroring SEPs, and hence, the elevated intensities at or after their passage were not observed.

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