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PARTICLES AND FIELDS

Approaching Solar Maximum 24 with STEREO—Multipoint Observations of Solar Energetic Particle Events

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Abstract Since the beginning of the Solar Terrestrial Relations Observatory (STEREO) mission at the end of 2006, the two spacecraft have now separated by more than 130° degrees from the Earth. A 360-degree view of the Sun has been possible since February 2011, providing multipoint in situ and remote sensing observations of unprecedented quality. Combining STEREO observations with near-Earth measurements allows the study of solar energetic particle (SEP) events over a wide longitudinal range with minimal radial gradient effects. This contribution provides an overview of recent results obtained by the STEREO/IMPACT team in combination with observations by the ACE and SOHO spacecraft. We focus especially on multi-spacecraft investigations of SEP events. The large longitudinal spread of electron and ^{3}He-rich events as well as unusual anisotropies will be presented and discussed.

Keywords Solar energetic particle (SEP) events

1 Introduction

The twin-spacecraft Solar Terrestrial Relations Observatory (STEREO) mission is dedicated to a variety of scientific topics like coronal mass ejection (CME) initiation and propagation as well as a better determination of the structure of the ambient solar wind. Another important subject is to discover the mechanisms and sites of solar energetic particle (SEP) acceleration in the corona and in the interplanetary medium. In this work, we present highlights and recent results obtained with the STEREO spacecraft, addressing the latter topic of solar energetic particle events. SEPs carry fundamental information on acceleration and propagation processes in the corona and in the interplanetary medium. To disentangle acceleration and transport effects and to judge the importance of various proposed mechanisms are the subjects of the recent research. SEP events have been observed and studied with space-borne instrumentation for more than half a century and have been found to be associated with flaring active regions at the Sun or shock waves. Energetic particles are accelerated to high energies in flares which have been treated as point-like sources from where the SEPs propagate outwards along the Parker magnetic field lines. Assuming a small degree of scattering, this scenario leads to an impulsive SEP event observed by a well-connected observer but not by a spacecraft which is separated by more than 20° to 40° in longitude. Figure 1 shows an example in the upper part where STEREO A observed an event with a longitudinal separation angle of 9.8° but STEREO B and Advanced Composition Explorer (ACE) which are separated by more than 60° do not detect the event. Contrary to a flare, a coronal or CME-driven shock may act as an extended source region generating wider SEP distributions [3, 17, 29, 33]. A further process, which may broaden the SEP spread and may even

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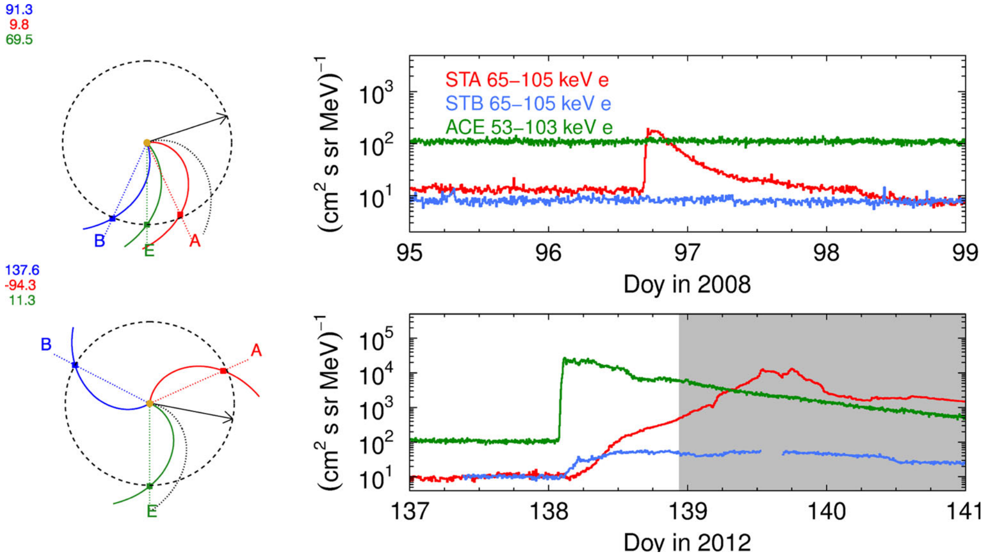

Fig. 1 Near relativistic electron measurements by STEREO A (*red*), STEREO B (*blue*), and ACE (*green*) during a narrow spread event (*top panel*) and a widespread event (*bottom panel*). The longitudinal configurations of spacecraft position and magnetic footpoints and the flare position are shown on the left. While the event shown in the upper panel is only observed by STEREO A and not by the other two spacecraft at longitudinal separations of 69° and 91° (see upper left edge of the diagram), the event in the lower panel is observed by all three spacecraft with a maximum separation angle of 138° for ACE. The *shaded area* marks a period of strong ion contamination at STEREO A saturating the electron intensities

be responsible for widespread SEP events, is efficient perpendicular diffusion in the interplanetary medium [6, 9, 11].

To study the longitudinal extent of an event, multiple spacecraft, well separated in space, are needed. Furthermore, to make the solar association, the Sun's surface has to be observed. These observations were very limited during the Helios and Ulysses era due to the lack of remote sensing instrumentation aboard the spacecraft and only an associated active region (AR) visible from Earth could be unambiguously identified. The two STEREO spacecraft are equipped with remote sensing and in situ instrumentation with unprecedented sensitivity and cadence (see Section 2). The growing longitudinal separation angle of the two spacecraft makes this mission unique to investigate SEP events, especially in terms of their longitudinal extent and variations, respectively. Ground-based instrumentation and close to Earth spacecraft such as ACE, Solar and Heliospheric Observatory (SOHO) , or WIND lend themselves to add a third viewpoint to the STEREO observations. This provides a set of measurements taken at almost the same heliocentric distance avoiding radial gradient effects which were present during the Helios mission. Now, from all these three viewpoints, the Sun's surface and corona are imaged, making it possible to unambiguously identify the source ARs at the Sun which are associated with the SEP events. To know the exact source position and to exclude additional source, candidates are indispensable when studying acceleration or propagation mechanisms of SEPs. In February 2011, the STEREO spacecraft exceeded a separation of 90° from Earth, making it possible at one time to image the full Sun's surface.

The STEREO spacecraft unambiguously proved the existence of extremely wide SEP spreads almost all around the Sun (c.f. [9]). The lower panel of Fig. 1 shows energetic electron measurements of the first (and so far only) ground level event (GLE) [13, 36] of the current solar cycle which is another example of a widespread SEP event. Energetic particles are observed at all three spacecraft (STEREO A and B, and ACE), although only ACE is well connected to the source active region. The STEREO spacecraft are separated far from the flare longitude with STEREO B having a longitudinal (flare to footpoint) separation angle of ∼140°. Note that the shaded area marks the period when STEREO A electrons are strongly contaminated by ions distorting the electron measurement. Interestingly, this event shows an asymmetry in propagation time of the SEPs: Although STEREO A is closer to the source active region and observes a higher SEP increase, the onset of the energetic electrons (and other SEPs, not shown) is later than at STEREO B [14].

As has been discussed above, several ideas exist to explain wide longitudinal distributions of energetic particles. However, there is still a strong debate on the different proposed scenarios, and it is not clear if only one or multiple processes are involved in producing these wide distributions. The spread of the SEPs could happen close to the Sun due to a large coronal shock [2, 4] building an extended source region or due to a coronal transport process like the spreading of magnetic field lines below the source surface [19]. An extended source region formed by a wide CME-driven shock [2, 18, 33, 38] or efficient perpendicular diffusion of the SEPs [6, 7, 11, 40] are further possible processes acting in the interplanetary medium. Coronal disturbances, called EUV waves, which are initiated by a flare and run over the solar surface have also been proposed to be linked to the energetic particle distribution [20, 34]. To disentangle the above processes, one needs comparable multipoint measurements of the same event and a sufficient angular coverage which is uniquely provided through the STEREO mission.

2 The STEREO Mission and Instrumentation

The twin STEREO spacecraft were launched in October 2006 [16] and are equipped with nearly identical remote sensing and in situ instrumentation. Both satellites perform heliocentric orbits following the motion of the Earth in the ecliptic plane with one spacecraft moving ahead of the Earth (STEREO A) and the other one trailing behind (STEREO B). The longitudinal separation angle between both spacecraft grows about 44° to 45° per year. By July 2013, each of the two spacecraft was separated about 140° from Earth, spanning an angle from each other of 80° on the backside of the Sun as seen from Earth. The remote sensing instruments are combined in the SECHHI instrument suite [15] which contains the extreme ultraviolet telescope EUVI (nominal cadence 4 min) [42], the coronographs (COR1 and COR2 instruments [37], nominal cadence 8 and 15 min, respectively), and the heliospheric imagers HI (nominal cadence 60 min for HI1 and 120 min for HI2) [8]. Solar wind plasma data are provided by the PLASTIC instrument [12]. For SEP investigations, the most essential instruments are the energetic particle telescopes (HET, SEPT, LET, and SIT) hosted by the IMPACT instrument suite [28] which also contains the MAG instrument measuring the interplanetary magnetic field [1]. The Low-Energy Telescope (LET; [30]) measures protons and heavy ions $2 \leq Z \leq 28$ at 1.8 to 100 MeV/nucleon. The Solar Electron and Proton Telescope (SEPT; [32]) measures electrons from 30 to 400 keV, and ions from 30 keV to 6 MeV. The High Energy Telescope (HET; [39]) provides energetic electron measurements in the range from 1 to 6 MeV and proton measurements from 13 to 100 MeV, respectively. Anisotropy measurements are performed by the LET and SEPT instruments.

3 The Rising Phase of Solar Cycle 24

The two STEREO spacecraft were launched in 2006 during solar minimum conditions. Solar activity was still decreasing and reached its minimum of this very unusual and deep solar minimum in December 2008. Also, the rising phase of solar cycle 24 was relatively weak, producing only very few SEP events until 2010. The upper part of Fig. 2 shows the sunspot number from year 2000 up to now which illustrates the last solar activity minimum and the rising phase of cycle 24. At the beginning of 2011, SEP events got more frequent and more intense. The lower panel of Fig. 2 shows the results of a 3-point survey of SEP events from mid-2010 through mid-2013 [31]. The survey identified a total of 44 SEP events that satisfied the NOAA criterion of >10 “proton flux units” (10 protons/(cm^2-sr-s) with energies >10 MeV) at one or more locations (STEREO A, STEREO B, and Earth). This included 24 single-spacecraft events, 13 two-spacecraft events and 7 three-spacecraft events (see dates above the peaks in Fig. 2 panels). It is interesting that 16 % of the >10 proton flux-unit detections were due to events that originated beyond the solar limb as viewed by that spacecraft.

4 STEREO Highlights and Recent Results

4.1 The Longitudinal Variation of SEP Peak Intensities

With STEREO, it is possible to observe the same event from multiple, well-separated points. While the two spacecraft are practically at the same heliocentric distance as the Earth and their absolute heliographic latitude does not exceed 7 degrees, the longitudinal separation steadily grew since the launch of the spacecraft. If such multipoint observations are available, one can study the longitudinal extent of the event and determine the longitudinal variation of event key characteristics. Figure 3 shows 71–112 keV electron peak intensities observed by the three spacecraft as a function of the longitudinal (flare to magnetic footpoint) separation angle (see [21]). Observations of the same event are connected by lines, and the different spacecraft are marked by different colors with STEREO A in red, STEREO B in blue, and ACE in black, respectively. Obviously, the highest peak intensity is usually observed by the spacecraft with the smallest separation angle (close to zero on the horizontal axis) and peak intensities decrease with increasing separation angle. Lario et al. [21] use the functional form $j = j_0 \exp\left[-(\Phi - \Phi_0)^2/2\sigma^2\right]$ to describe the longitudinal (Φ) variation of the peak intensities j observed at 1 AU. Here, j_0 is the maximum peak intensity of the distribution at a separation angle Φ_0. The authors find a mean standard deviation of $\sigma = 49° \pm 2°$. They also analyzed the peak

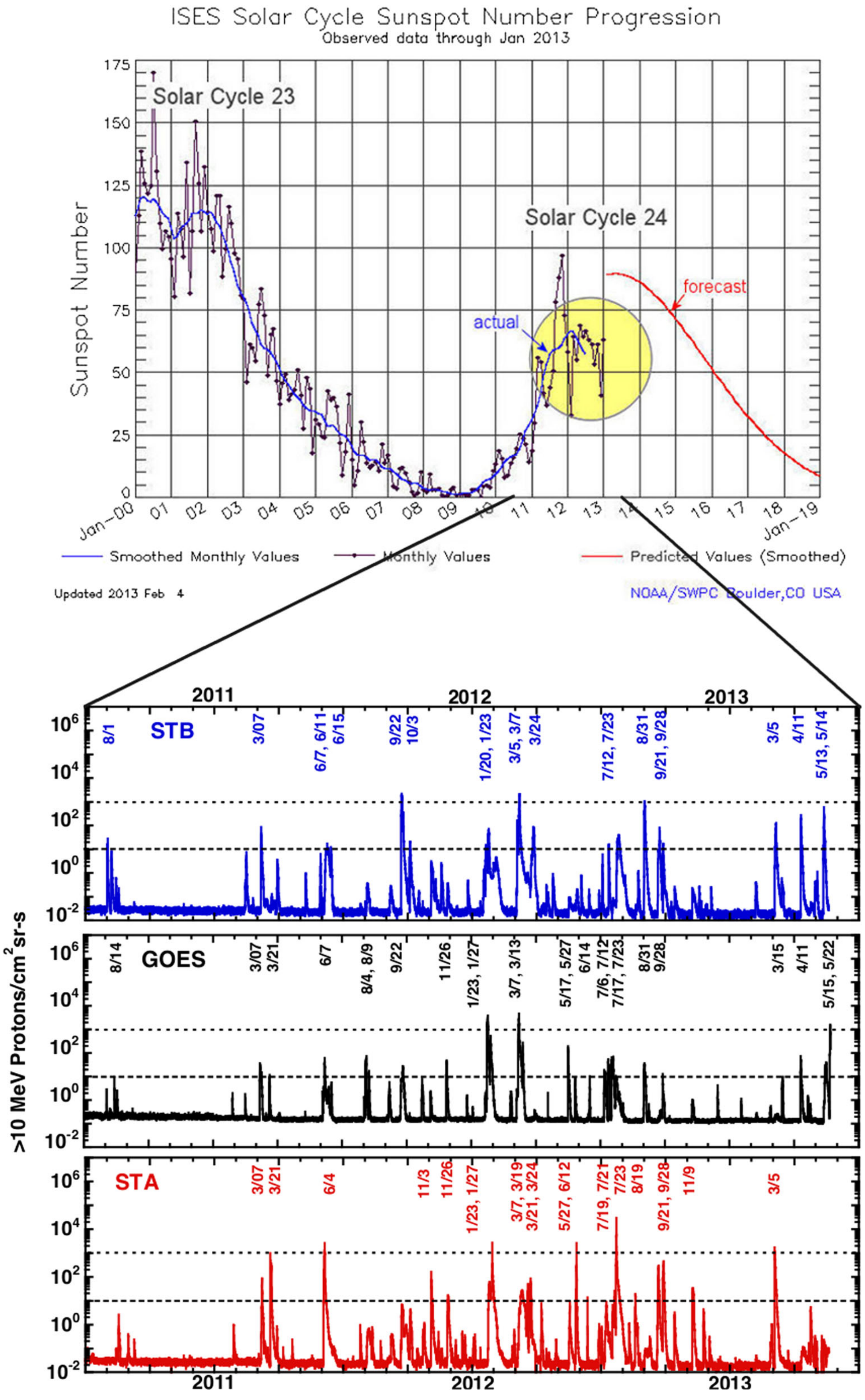

Fig. 2 *Upper figure*: smoothed monthly sunspot number during the period from January 2000 to January 2013 (NOAA/SWPC Boulder, CO USA). *Lower figure*: >10 MeV proton intensities measured by STEREO B LET and HET (*blue*, *upper panel*), GOES (*black*, *middle panel*), and STEREO A LET and HET (*red*, *bottom panel*) during the rising phase of solar cycle 24 (July 2010–June 2013; from [31])

intensities of (1) 0.7–3.0 MeV electrons, (2) 15–40 MeV protons, and (3) 25–53 MeV protons and determine standard deviations of (1) $\sigma = 46° \pm 2°$, (2) $\sigma = 43° \pm 2°$, and (3) $\sigma = 45° \pm 1°$, respectively. Previous studies using Helios and IMP-8 data obtained a smaller standard deviation of $\sigma = 36° \pm 2°$ for 27–37 MeV protons [23] which may indicate that the particle events spread effectively in longitude with increasing radial distance. However, a differ-

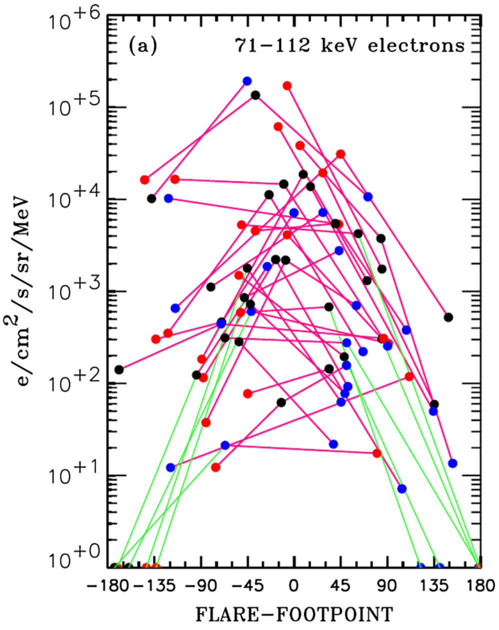

Fig. 3 Event peak intensities of 71–112 keV electrons measured by STEREO A (*red*), STEREO B (*blue*), and ACE (*black dots*) as function of the longitudinal flare to footpoint separation angle. Observations of the same event are connected by *magenta lines*, *green lines* connect to those spacecraft which did not observe any particle increase. Figure adopted from [21]

ent sample of events was used with Helios in solar cycle 21, which could also cause this difference.

4.2 SEP Events Showing Large Longitudinal Particle Spreads

The great new capabilities of the STEREO mission provided the tools to unambiguously identify and to study several widespread SEP events (c.f [9, 34, 41]). Also, the first GLE, which so far is the only GLE of solar cycle 24, is a widespread event (c.f. Fig. 1 bottom panel and [14]). The processes leading to the wide SEP distributions are still under discussion, and it is not clear if these processes vary from event to event or if several processes are involved. However, it is now clear that widespread SEP events occur more often than expected from Helios observations and spreads almost all around the Sun are possible [9]. Dresing et al. [10] studied a set of 19 widespread SEP events observed with STEREO and ACE and estimated the longitudinal broadness of the events at 1 AU. Different from the range spanned by the three spacecraft observing the event, the broadness is the longitudinal range over which a significant SEP increase is detectable. For this purpose, the peak intensity distribution (like in Fig. 3) for each event was assumed to be symmetric around 0° separation angle and approximated by the form $I(\phi) = I_0 \exp[-\phi/2\sigma^2]$. Here, I_0 is the peak intensity at 0° separation angle ϕ, and σ the standard deviation. The broadness is now determined by the angular range spanned by the fitted curve until it reaches a background value (Fig. 1 in [10]). Figure 4 shows the theoretical curves of maximum intensity I_0 vs. σ marking a broadness of 180°, 300°, and 360°, respectively. The points for the events which were well described by the fit are added to that figure and lie all above a 180° spread with two points exceeding a 300° spread and one point even exceeding the 360° spread. Note that the selection criteria excludes events with broadnesses below 160° which is marked by gray shading in Fig. 4.

An additional unexpected result from the combined STEREO and ACE SEP measurements is the observation of ^{3}He-rich events over wide longitudes. The 7 February 2010 event was observed by all three spacecraft, spanning over 130° in longitude [41]. Figure 5 shows the 2.3–3.3 MeV/nuc ^{3}He fluence observed by the different spacecraft as function of the longitudinal (flare to footpoint) separation angles. The observations are fitted well by a Gaussian with a standard deviation of σ =∼ 48° [41]. Such ^{3}He-rich SEP events originate from solar flaring regions and previously had only been observed when the longitude of a spacecraft was within ∼20° of the source region, suggesting a typical longitudinal spread more than a factor of two smaller than that observed in the 7 February 2010 event. In an effort to determine whether wide ^{3}He-rich events occur under only certain conditions, Cohen et al. [5] examined seven ^{3}He-rich SEP events of similar size but only observed by a single STEREO spacecraft. ACE and the other STEREO, which did not observe the event, were used as upper limits. In that sense, the authors determined

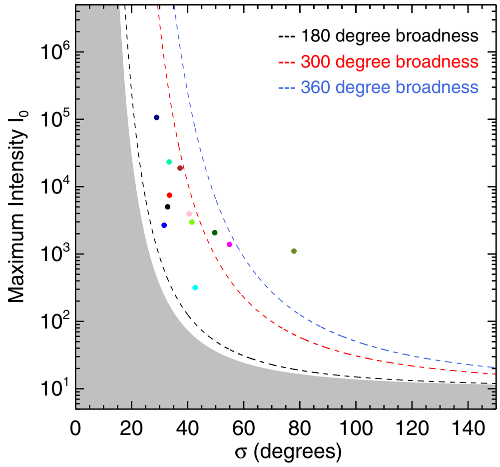

Fig. 4 Fit-values I_0 vs. σ, from fitted maximum intensity distributions of widespread STEREO and ACE events. The *dashed lines* represent the theoretical I_0-σ combinations for longitudinal broadnesses of 180°, 300°, and 360°, respectively. The *gray shaded area* marks broadnesses $\leq$ 160° and cannot be filled by the set of events due to the selection criteria

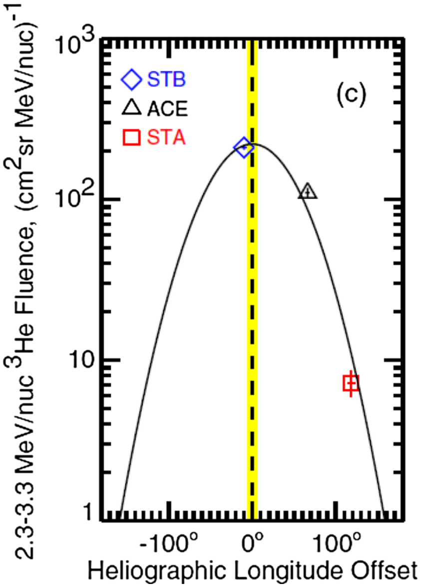

Fig. 5 ^{3}He fluences measured by STEREO B (*blue*), STEREO A (*red*), and ACE (*black*) during the 7 February 2010 SEP event as function of the longitudinal separation angle (of flare to spacecraft magnetic footpoint). A Gaussian fit, centered around 0°, with a standard deviation of $\sigma = 48°$ fits to the data. Adopted from [41]

the widest Gaussian (centered on the flaring AR) consistent with the observed ^{3}He fluence and the upper limits. Figure 6 shows an example on 11 November 2010 where only STEREO B observed the event but STEREO A and ACE did not, leading to a maximum standard deviation between 15° and 25° [5]. In total, these single-spacecraft events were found to be significantly narrower than multi-spacecraft ^{3}He-rich events [5]. Examination of the occurrence of preceding CMEs suggests that wide CMEs may play a role in spreading the ^{3}He to yield a multi-spacecraft event; typically, the single-spacecraft events did not have preceding CMEs that were >90° (the exceptions were very slow), while the 7 February 2010 event was preceded by a halo CME.

4.3 The Extreme July 23, 2012 SEP Event

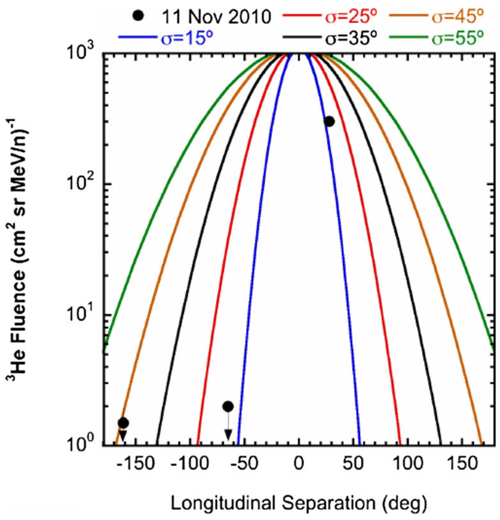

Fig. 6 ^{3}He fluences vs. longitudinal (flare to footpoint) separation angle for the 11 November 2010 event detected by STEREO B; upper limits are shown for ACE and STEREO A at their respective separation angles. The *lines* show Gaussian distributions of different sigmas. Only a Gaussian with a sigma less than 15–20 is consistent with the data. Adopted from [5]

By far, the most intense of the events observed during cycle 24 occurred on July 23, 2012, following an eruption at ∼W140° that included a >3,000- km/s CME and a record-breaking solar wind speed of 2,200 km/s at STEREO A. Figure 7 shows the time history of the event in seven energy intervals. Had Earth been in the STEREO A location, the >10 MeV peak intensity of 35,800 protons per cm^2-sr-s would be third on the list of the most intense SEP events during the GOES era (1976–2013); topped only by 1992 March 23 and 1989 October 20 with 43,000 and 40,000 intensity units, respectively. The July 23 event is a rare example of a SEP-mitigated shock in which the SEP pressure at one point exceeded the magnetic field pressure by a factor of >70 (see [35]). In this sense, it is similar to the October 20, 1989 event studied by [22]. Had the July 23 event been aimed at Earth, it would have produced a geomagnetic storm with an estimated DST of >1,000 nT [35].

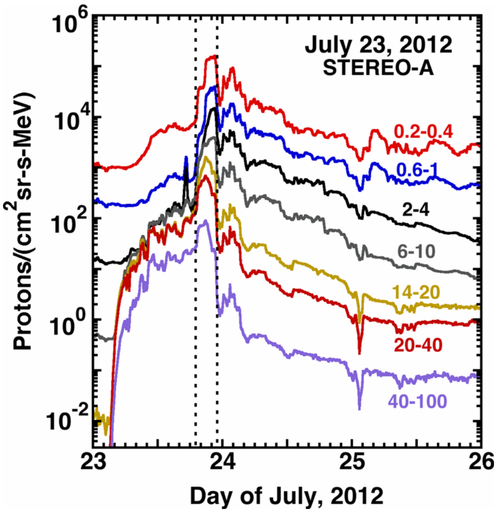

Fig. 7 Proton intensity during the July 23, 2012 event as measured by the SEPT (0.2–1 MeV), LET (2–10 MeV), and HET (14–100 MeV) instruments [31]. The *dotted lines* indicate the period during which the magnetic field strength suddenly dropped and the SEP intensities simultaneously increased at all energies, resulting in an SEP pressure that became 70 times greater than the magnetic pressure. The >10 MeV proton intensity reached a maximum of 35,800 protons/(cm^2-sr-s), the third largest observed at 1 AU since 1972

4.4 Unusual Anisotropies Observed by STEREO

Instruments on STEREO observe a large variety of SEP anisotropies. Unidirectional beamed distributions often appear at the onset of magnetically well-connected events, while bidirectional flows are seen within several interplanetary coronal mass ejections (ICMEs) arising from injection of particles at both footpoints of the CME or mirroring of a unidirectional beam. The LET instrument detected extremely large bidirectional anisotropies in 4–6 MeV protons at STEREO A on 2010 August 18 while inside a magnetic cloud; intensities along the field direction were nearly 1,000 times greater than those perpendicular to the field [24]. At other times, distributions with large depletions at 90° to the field or those that instead are peaked at 90° (i.e., trapped distributions) have also been seen [25–27]. Several examples of loss-cone distributions have been observed, where particles with large pitch angles are reflected by a magnetic field constriction, while those with smaller pitch angles are not if the field strength is not large enough to turn them around. A dramatic example of a loss-cone distribution (Fig. 8) appeared on 2012 July 24 [26, 27] at STEREO B, associated with an SEP event that was extremely large at STEREO A (see Section 4.3). In this case, the incident beam was flowing toward the Sun from a shock that was radially beyond STEREO B at 1 AU. Quantitative analysis of these and other pitch angle distributions from STEREO and comparison with theory and models should help to reveal insights into energetic particle transport in these interesting SEP events.

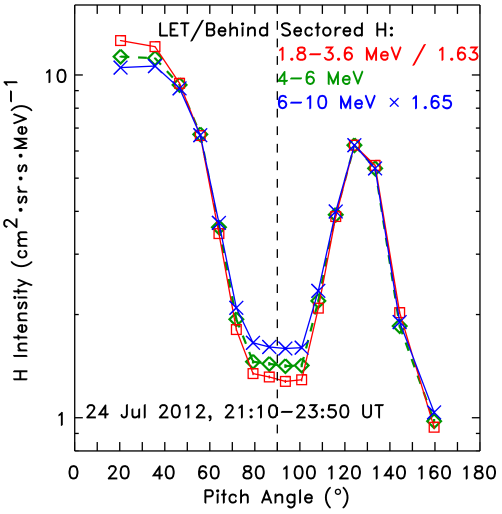

Fig. 8 Pitch angle distributions for protons in three energy bands from LET on STEREO B. An incident beam at ∼ 0° is partially mirrored, but particles near 180° are missing, forming a loss-cone distribution

5 Summary and Concluding Remarks

After nearly 7 years in space, the two STEREO spacecraft have delivered a new and unique set of Solar Energetic Particle (SEP) events observed at 1 AU. While radial gradient effects can be excluded, the new and up-to-date instrumentation of in situ and remote sensing experiments forms a perfect platform for SEP investigations, especially when combined with close to the Earth observations. The first years of the STEREO mission were situated during the very deep solar minimum of cycle 23 and the slowly rising phase of cycle 24. Although the current cycle was relatively weak, showing only one GLE up to now, an extremely intense proton event has been detected by STEREO A on 23 July 2012 [31, 35], which was the third intense >10 MeV proton event ever observed at 1 AU. SEP activity began to rise in 2011 when each of the two spacecraft had already separated by 90° from Earth. With this separation, the full Sun's surface was imaged at once for the first time ever and STEREO was perfectly prepared to unambiguously identify the SEP associated source active regions at the Sun. In contrast to previous space missions, STEREO is uniquely capable to identify and detect widespread SEP events and to study the longitudinal variances of these events. Widespread events appear to be more frequent than expected and show longitudinal broadnesses exceeding 300° to 360° [9, 10, 14]. A great surprise was also the observation of ^{3}He at longitudinal separation angles (of magnetic footpoint to parent active region) of ∼120° [41]. Especially, these ^{3}He-rich events had been believed to be flare-associated with longitudinal spreads below ∼40° at 1 AU [33]. The fact that widespread SEP events were observed more often by STEREO than before is likely because previous missions were not so well suited to detect them. Nevertheless, extremely widespread events are rather seldom and it is likely that they have to be accompanied by special conditions. This is also suggested by [5] who compared the extreme ^{3}He-rich event from 7 February 2010 with the more frequent single STEREO observations showing much smaller longitudinal spreads. Cohen et al. [5] propose pre-event CMEs to play a role for the wider spreading.

Beside STEREO's great multi-spacecraft capabilities, single-spacecraft observations can improve our understanding of the interplanetary magnetic field variability and configurations, which can strongly influence the propagation of SEPs. The resulting unusual particle anisotropies observed with STEREO show evidence for reflecting boundaries behind the spacecraft, trapped particle distributions [27], and even for large magnetic clouds connecting to a source region close to the Sun [24]. Each SEP event is certainly determined by a combination of acceleration and transport effects. Which mechanisms exactly lead to wide SEP distributions is still under discussion. If these mechanisms change from event to event or if a combination of processes has to be involved must be addressed in future studies.

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