Observations of Broad Longitudinal Extents of $^3$He-rich SEP Events

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Abstract: The widths of $^3$He-rich solar energetic particle events have been studied using data from ACE and the two STEREO spacecraft, and individual events detectable over $>60^\circ$ in heliographic longitude were found to be relatively common. The event of 7 Feb 2010, which was detected at all three spacecraft when they spanned $136^\circ$ in heliographic longitude, is discussed in detail. The $^3$He fluence is a strong function of the longitudinal separation between the observer’s magnetic connection point at the Sun and the solar source region. The relationship between these conclusions and results of previous studies of the distribution in heliographic longitude of x-ray flares associated with single-spacecraft detections of $^3$He-rich events is discussed, as are possible physical mechanisms for longitudinal spreading of energetic particles.

Keywords: solar energetic particles, $^3$He-rich SEP events, interplanetary transport, STEREO, ACE

1 Introduction

According to a widely accepted paradigm, solar energetic particles (SEPs) originating from reconnection-driven acceleration in solar flare events escape into the heliosphere along open magnetic field lines that are involved in the reconnection. The small spatial extent of the reconnection region implies that the group of field lines populated with energetic particles in the solar corona should be narrow. Even after expansion into the heliosphere, this set of field lines should span a rather limited solid angle.

In the interplanetary medium, flare-associated events are commonly identified based on their large enhancements of $^3$He. Studies of the locations of x-ray flares associated with $^3$He-rich SEP events detected near Earth [1, 2, 3] found distributions centered at a heliographic longitude $\sim 55$–$60^\circ$ west, the best connected longitude for a Parker-spiral magnetic field in the slow solar wind. As illustrated in Figure 1, the most statistically-significant of these studies [2] obtained an approximately Gaussian distribution in heliographic longitude with rms width $\sigma \approx 15$–$20^\circ$, but the distribution contained a few events with longitudinal separations $> 3\sigma$ from the mean.

A few studies combining data from Helios-1 and -2 and near-Earth spacecraft investigated the longitudinal widths of flare-associated SEP events based on detections of $^3$He or electrons, which are commonly accelerated in such events. There was at least one indication [4] of an event in which $^3$He was observed over a significantly wider range of longitudes than expected based on the single-spacecraft studies, but uncertainty about whether the same event was observed at the different spacecraft prevented the authors from challenging the prevailing view that the typical angular width of $^3$He-rich events is relatively narrow. On the other hand, multispacecraft detections of energetic electron events [5] showed clear examples of events detectable at spacecraft separated by at least $80^\circ$.

NASA’s two STEREO spacecraft, launched in October 2006, are orbiting the Sun at a distance of approximately 1 AU with their heliolongitudinal distance from Earth increasing at a rate of $\sim 22.5$°/year, with STEREO-A leading the Earth and STEREO-B trailing. By February 2011 the STEREOs had separated by $\sim 90^\circ$ from Earth.

We have used energetic particle detectors on the STEREOs [6] and on ACE [7], which orbits the Sun near the Sun–Earth L1 Lagrange point, to investigate the longitudinal extent of individual flare-associated SEP events that occurred from January 2007 through January 2011. This 4-year period coincided with the unusually long, quiet solar minimum between solar cycles 23 and 24. Although the low level of solar activity resulted in only a small number of $^3$He-rich events that could be studied over the first three
of these years, it also significantly reduced the probability of chance coincidences between \(^3\)He-rich event detections at different spacecraft. We have previously reported [8] on one event (3–4 Nov 2008) in which \(^3\)He was detected at ACE and STEREO-B when they were separated by 41° and in which electrons were detected at all three spacecraft.

2 Observations

Events were selected for the present study by examining \(^4\)He mass spectrometers from the Low Energy Telescope (LET) instruments on STEREO-A and STEREO-B and identifying periods with \(^3\)He intensity enhancements over the background level, which is due to galactic cosmic ray \(^3\)He that has had its energy reduced by solar modulation. The LET data sets were examined in the energy intervals 2.3–3.8 MeV/nuc and 3.8–8.0 MeV/nuc. Most of the \(^3\)He-rich event identifications were made in the lower energy interval where the SEP intensity tends to be higher and the background lower. In a few events there was enough spill-over from \(^4\)He into the \(^3\)He mass interval so that the presence of a \(^3\)He increase could not be established below 3.8 MeV/nuc. In a few such cases, data from the higher energy interval permitted identification of \(^3\)He-rich events.

For time periods having \(^3\)He increases in at least one of the STEREO/LETs, data from the ULEIS and SIS instruments on ACE were then checked for nearly coincident \(^3\)He increases. In small SEP events of the type considered in the present study, the energy coverage by the ACE instruments is primarily below (ULEIS) and above (SIS) the 2.3–3.8 MeV/nuc interval that we have focused on from the LETs. Since the \(^3\)He intensity tends to decrease rapidly with increasing energy, we find a number of additional time periods in which a \(^3\)He increase is observed in the low-energy data from ULEIS but with no corresponding detection in SIS or in the STEREO/LETs. These lower-intensity events have not been considered in this investigation. In some cases the higher sensitivity to \(^3\)He-rich events provided by the low-energy response of ULEIS was essential for the near-Earth detection of events observed at one of the STEREOs.

We also examined heavy-ion data in the energy range 0.32–0.45 MeV/nuc from STEREO/SIT and ACE/ULEIS to determine whether the \(^3\)He increases were accompanied by heavy-ion increases having an enhanced Fe/O ratio, another characteristic of flare-associated SEP events. Finally, we used measurements of 70–100 keV electrons by STEREO/SEPT and ACE/EPAM to check for accompanying energetic electron events.

Table 1 shows the number of \(^3\)He-rich SEP events detected at either STEREO-A or -B in successive half-year intervals. The numbers are subdivided according to how many of the three spacecraft detected the event. The early time intervals occurred during the quietest portion of the cycle 23/24 solar minimum and \(^3\)He-rich events were nearly absent. During the more recent time intervals a substantial fraction of the \(^3\)He-rich events were also detected at ACE, in spite of its large longitudinal separation from the STEREOs (>60° since late 2009). A few events were detected at all three spacecraft; the best example of such an event is discussed in the following paragraphs.

Figure 2 shows \(^3\)He and electron intensity versus time plots from the event of 7 Feb 2010 when STEREO-A was leading the Earth 65° in heliographic longitude and STEREO-B was trailing by 71°. The source of this event was associated with an active region (AR11045, located at N23W01 at 00:00 UT on 8 Feb 2010) that produced a large number of x-ray flares (Fig. 2c) as well as several type III radio bursts and energetic electron events. In addition, a slow (∼425 km/s) halo CME was observed starting around 03:54 on 7 Feb 2010 [9]. Around the time of all this activity there were three other active regions on the solar disk, but only AR11045 was flaring. A Parker-spiral magnetic field originating from AR11045 would connect to ~60° at 1 AU, which is close to the STEREO-B location. This event was preceded by another \(^3\)He-rich event from the same active region approximately a day earlier. Comparing onset times for the \(^3\)He and the electrons it is apparent that the \(^3\)He-rich...
injection we are discussing was not directly associated with the two major electron injections, but it may correspond to a minor electron increase observed late on 7 Feb 2010.

Instruments on all three spacecraft observed $^3$He from the event in spite of the 136° longitudinal separation between the two STEREOs. With increasing separation from the well-connected longitude we observe a decrease of both the $^3$He fluence and peak intensity as well as increasing delays of the onset and peak times. It is evident that these delays, although not precisely determined, are significantly longer than the ~2 hr required for propagation to 1 AU with 0° pitch angle and an energy ~3 MeV/nuc. An enhanced Fe/O ratio (>0.75) at ~0.4 MeV/nuc was also observed at STEREO-B and ACE, but the event was too weak at STEREO-A to allow a measurement of Fe/O.

Figure 3 shows the longitudinal dependence of the 2.3–3.8 MeV/nuc $^3$He fluence. The two STEREO data points were measured with the LET instruments while the ACE data point was obtained by interpolating between measurements from ULEIS and SIS at lower and higher energies, respectively, to obtain the ACE fluence for this same energy band. The intensity calibrations of the STEREO and ACE instruments had previously been checked against one another using data from a $^4$He-rich event that occurred when all three spacecraft were located near Earth [8]. The smooth curve in Figure 3 shows a fit to the three data points using a Gaussian constrained to be centered at the well-connected longitude. The rms width of this Gaussian is 47°. A very similar Gaussian is obtained when the data are fitted without the constraint.

### 3 Discussion

Observations of energetic particle flux “drop-outs” in $^3$He-rich SEP events [11] have demonstrated that diffusive transport of energetic particles transverse to the heliospheric magnetic field is inefficient at distributing the particles in heliographic longitude. Thus we discount this as a possible mechanism for producing the large longitudinal spread that we observe.

The small clusters of open magnetic field lines along which accelerated particles escape from the reconnection region of a flare are expected to undergo expansion and possibly some angular displacement as they pass through the corona. Potential field source surface (PFSS) model calculations [12] provide a means for estimating the magnitude of these effects. We have examined 12 years of daily PFSS maps and found no instances in which field lines from a localized region at the photosphere (<10° diameter) expanded to cover a range of longitudes on the heliographic equator that was as broad as the 136° spacing between the two STEREO spacecraft at the time of the 7 Feb 2010 event. Even recognizing that each PFSS field map is based on data from a full solar rotation and thus cannot be expected to accurately reproduce features in the field that are changing on significantly shorter time scales, we think it is unlikely that the expansion of a quasi-static magnetic field between the photosphere and the upper corona is the major contributor to the broad longitudinal spreads observed in some $^3$He-rich SEP events.

Coronal mass ejections (CMEs) are now known to occur in coincidence with some $^3$He-rich SEP events [11], although they tend to be slower and/or narrower than those that drive shock acceleration in large, gradual SEP events. It is possible that coronal and interplanetary magnetic fields could be distorted by a CME (either associated with the event of interest or with a preceding event) and thus affect the lon-
longitudinal transport of energetic particles, even if the CME itself is not responsible for particle acceleration. As noted above, a slow halo CME did occur early on 7 Feb 2010. That CME, or one of several narrower CMEs that where observed later that same day [9], may have affected the longitudinal distribution of energetic particles in the heliosphere. Determining whether CMEs generally play a significant role in the longitudinal transport of the energetic particles from He-rich events will require a survey of additional He-rich periods.

There have been a number of observations of “sympathetic” solar flares in which the occurrence of one flare apparently triggers a subsequent flare in a region on the Sun that in some cases can be well separated from location of the original flare, as discussed in [13] and references therein. Such effects, which may be related to magnetic connections between widely spaced active regions or to transport of magnetic disturbances by waves in the corona, are a conceivable source of nearly simultaneous He-rich events with large longitudinal separations. However, as illustrated in the lower panel of Figure 2 and also in [8], multiple energetic-electron events are sometimes observed in conjunction with the He-rich events and the electron event onset times and relative intensities in these sequences are similar at widely space spacecraft. This similarly strongly suggests that energetic particles being observed at the different locations are coming from the same acceleration events on the Sun.

Recent advances in modeling the distribution of open magnetic fields above the solar photosphere (e.g., [14] and references therein) have led to the realization that the field structure can be topologically very complex, containing narrow (or even singular) corridors of open field connecting widely separated coronal holes. This large-scale, complex boundary between open and closed field regions might provide conditions conducive to reconnection events that could generate energetic particles access to widely separated heliographic longitudes. If this turns out to be the case, energetic particle observations may provide an important tool for probing the characteristics of this magnetic structure.

Given the strong dependence of He intensity on longitudinal separation from the well-connected field line (Fig. 3), it is clear that He-rich events with fluences near the sensitivity threshold of an instrument will be detectable only when that separation is small. The distribution of the longitudes of flares associated with He-rich SEP events detected at a single location will be affected by this sensitivity-related bias, resulting in a width narrower than the actual longitudinal spread of these events. To illustrate this effect we have assumed that the longitudinal dependence of the measured fluence, \(G(\Delta \phi)\), is the same in all He-rich events. In addition we have assumed that the distribution of event fluences, when observed at the well-connected longitude, has the form of a power-law with exponent \(-\alpha\). In this case the shape of angular distribution of flares associated with detected events is proportional to \(G^\alpha\). In this special case of a power-law event-size distribution the result is independent of the value of the instrument’s threshold for event detection. If the distribution \(G(\Delta \phi)\) is a Gaussian with standard deviation \(\sigma\), the distribution \(G^\alpha\) will also be a Gaussian, but with standard deviation \(\sigma/\sqrt{\alpha}\). Comparison of the Gaussian widths from Figures 3 and 1 does not, however, provide a reliable estimate of \(\alpha\) because the distribution in Figure 1 is also affected by differences in solar wind speed, which alter the Parker spiral, and because the distribution in Figure 3 was obtained from a single event that may not be typical.

Studies of additional He-rich SEP events using the STEREOs and near-Earth spacecraft should help determine how much event-to-event variation there is in the longitudinal dependence of event fluences. They should also address the question of whether event size and instrument sensitivity are the only limitations on the range of separations from the the well-connected longitude over which a given event can be detected. Quantitative comparison of event onset and rise times, particularly for energetic electrons, may also contribute to understanding the physical mechanism by which the particles accelerated in solar flares can be transported over a wide range of heliographic longitudes.

Acknowledgements: This work was supported by NASA at Caltech (under grants NNX08AI11G, NNX10AQ68G, and NNX10AQ68G, and through UC Berkeley under contract NAS5-03131), JPL, APL (under grant NNX10AT75G), and LMSAL. The STEREO/SEPT work was supported under grant 50 OC 0902 by the German Bundesministerium für Wirtschaft through the Deutsches Zentrum für Luft- und Raumfahrt (DLR).

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