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Furthering Our Understanding of Wide Longitude ^{3}He-rich SEP Events

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Abstract: With the significant separation between ACE and the twin STEREO spacecraft solar energetic particle (SEP) events can be observed simultaneously from substantially different longitudinal locations relative to the solar source. One of the surprising results from such multi-spacecraft studies is the observation of ^{3}He-rich SEP events over a wide longitude range. As these events are generally believed to originate from relatively small solar source regions (e.g., 5-10°), it was unexpected to observe them on multiple spacecraft spanning up to ~130 ° of longitude. Although the study of these events is ongoing, it is still not clear how the large longitudinal distribution is created. In an effort to further our understanding of these events, we have used the ACE and STEREO SEP data to identify seven single-spacecraft ^{3}He-rich events similar in peak intensity to those observed over wide longitudes. Given the absence of detection on two of the three spacecraft, we determined maximum standard deviations for the longitudinal spread of these events and found them to be significantly smaller than those of the multi-spacecraft ^{3}He-rich events. This indicates that the mechanism responsible for distributing the SEPs in longitude is variable and able to produce longitudinal distributions with a range of widths.

Keywords: solar energetic particles, particle transport, particle acceleration

1 Introduction

Not since the days when the Helios spacecraft were operational has there been the routine capability of studying solar energetic particle (SEP) events simultaneously from multiple vantage points - a capability that has returned with the launch of the twin STEREO spacecraft [1]. The energy and species coverage of the SEP measurements from STEREO are very similar to those available from sensors on ACE, making multi-spacecraft studies relatively straightforward. Although the four years following the STEREO launch in 2006 were very quiet in solar activity, it did provide the unique opportunity to study small SEP events for which the solar source was relatively easy to identify (often being the only visible flaring region on the Sun) and one could be reasonably confident that all three spacecraft were observing the same event. One of the surprising results that has emerged from such studies is the observation of small ^{3}He-rich events detected over >60° in longitude [2]. Prior work using single spacecraft observations suggested that observations of such events was limited to periods when the spacecraft's magnetic footpoint was within ~20° of the solar source [3].

The most well studied example of wide-longitude ^{3}He-rich SEP events is the 7 February 2010 event [2]. This event was detected by SEP instruments on both STEREO spacecraft and ACE even though the spacecraft positions covered 136° in longitude. That the event occurred during this period of low solar activity made it possible to not only identify the source region but verify that all three spacecraft were seeing the same event. A Gaussian fit to the ^{3}He fluences as a function of longitudinal separation between the solar source and the spacecraft's magnetic footpoints revealed a distribution with a standard deviation (sigma) of 48°. Additional observations of ^{3}He-rich SEP events over wide longitudes have been obtained, indicating that such occurrences are not unusual [2]. The possibility that the wide distribution was due to magnetic field line spreading between the photosphere and the corona was examined using the Potential Field Source Surface (PFSS) model and the results indicated this was unlikely to be the root cause. A number of other possible explanations were suggested, including the influence of coronal mass ejections (CMEs), cross-field diffusion, and sympathetic flaring, but the key mechanism responsible remains to be identified.

Recently Giacalone and Jokipii [4] modeled the effect of diffusion and solar rotation on the longitudinal spread of SEPs and specifically attempted to replicate the observations of the 7 February 2010 event. The authors were successful at matching the longitudinal distribution of the ^{3}He fluences with the assumption of a relatively modest value of the perpendicular diffusion coefficient. It was noted that the fact that the SEP events last for more than a day leads to the magnetic field lines being swept across a substantial longitude range due to the Sun's rotation. This combined with meandering of the field lines due to their footpoint motion on the Sun (represented by the perpendicular diffusion coefficient), yielded a fairly wide longitudinal distribution of SEPs.

As the ^{3}He fluence strongly decreases with increasing longitudinal separation from the source, it is possible that the large sigma obtained for the longitudinal distribution in the 7 February 2010 event is ubiquitous but was not observed in previous single spacecraft studies due to the limited sensitivity of the sensors used. Thus it would be particularly useful to identify ^{3}He-rich SEP events of similar peak intensity to the 7 February 2010 event in which

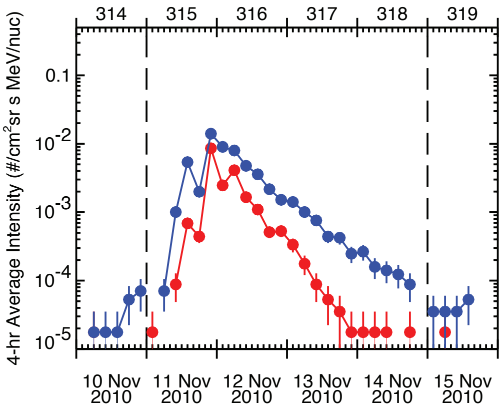

Fig. 1: ^{3}He (red points) and ^{4}He (blue points) intensities as a function of time for the 11 November 2010 event as observed by STEREO-B. Dashed lines indicate the time period of integration.

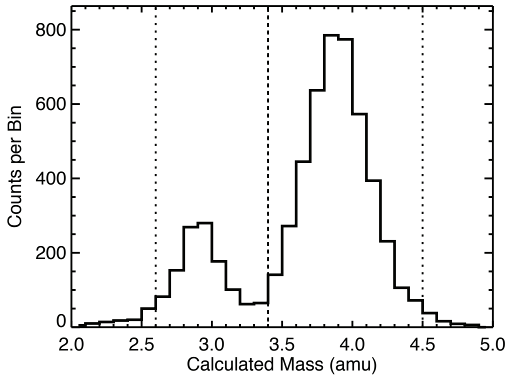

Fig. 2: Mass histogram for the 11 November 2010 event from STEREO-B; a peak at $\sim$3 corresponding to ^{3}He is clear. Data were selected to have total energies of 6.9-9.9 MeV (i.e, 2.3-3.3 MeV/n ^{3}He)

only one of the STEREO+ACE spacecraft yields a measurable fluence (the other two providing upper limits). Comparing the maximum sigma of a Gaussian consistent with the measured fluence and two upper limits to the sigmas of multi-spacecraft events would provide some indication as to whether the wide distribution of SEPs in the interplanetary medium is the norm or whether unique solar and/or interplanetary conditions are required.

2 Data Analysis

To identify such single-spacecraft events, we examined He mass spectrograms from the Suprathermal Ion Spectrometer (SIT; [5]) and the Low Energy Telescope (LET; [6]) on the STEREO spacecraft and the Ultra-Low Energy Isotope Spectrometer (ULEIS; [7]) and the Solar Isotope Spectrometer (SIS; [8]) on the ACE spacecraft. Seven events were selected that had clear enhancements of ^{3}He at intensities comparable to that observed in the 7 February 2010 event (typically peak intensities of $\gtrsim 10^{-2}$ particles/cm^2 sr sec MeV/n) on one of the two LETs, but none on either ACE instrument or the other LET. Figure 1 shows the ^{4}He and ^{3}He intensities as a function of time for one of the selected events (11 November 2010) and Figure 2 shows the event-integrated mass histogram with clear peaks corresponding to ^{3}He and ^{4}He. For each event, the ^{3}He fluence between 2.3 and 3.3 MeV/n was calculated from the event-integrated fluence spectra. These fluences, the integration time periods, and the detecting spacecraft are given in Table 1.

Upper limits from the other LET were calculated by integrating the observed ^{3}He intensities over the same time period and energy range. Determining an upper limit from the ACE data is more complicated as it requires interpolation between the ULEIS and SIS measurements as neither instrument measures the 2.3-3.3 MeV/n energy range. For the current work, we did not attempt this and instead used a background fluence value of 2 particles/cm^2 sr MeV/n, a value roughly consistent with the absence of a clear ^{3}He signal in the mass spectrograms.

We searched the 35-65 keV electron intensities from STEREO/SEPT to find increases occurring prior to each ^{3}He event and examined the radio data from the STEREO/SWAVES and Wind/WAVES sensors to determine the start time of the accompanying type III radio burst. This time was then used to guide our search for solar activity in the EUV movies available from SDO/AIA and STEREO/SECCHI (as well as the NOAA listing of GOES X-ray flares available through the Space Weather Prediction Center) in order to determine the location of the solar source region. The active region numbers and heliographic coordinates of these sources are given in Table 1; in a few cases, the source region was well beyond the west limb of the Sun as viewed from Earth and it was not possible to identify the active region number. In these cases we estimated the longitude of the active region from the STEREO/SECCHI EUV images.

Using the measured solar wind velocity and assuming the corresponding Parker spiral, we determined the solar longitudes of the magnetic footpoints of the spacecraft for each event. The longitudinal distribution of ^{3}He was calculated by plotting the observed fluence and two upper limit fluences versus the longitudinal separations between the solar source and the spacecraft footpoints; Figure 3 illustrates this for the 11 November 2010 event. This event was detected by STEREO-B whose footpoint was 28° east of the solar source region (AR 11123 at S26E08); ACE and STEREO-A at 65° and 162° westward, respectively, provide the upper limits. To determine the maximum sigma of a Gaussian consistent with the observations, Gaussians of different widths were centered on the active region longitude (i.e., a longitudinal separation of 0°) and scaled in height until consistent with both the measured fluence and the upper limit that provided the most stringent constraint. The resulting values for each event are given in Table 1. Figure 3 shows that a maximum sigma of $\sim$15-20° is consistent with the observations in the 11 November 2010 event.

As several of our events occurred during periods of increased activity it is quite possible that we failed to identify the correct solar source. Because of this, we also calculated the maximum sigmas using Gaussians centered at the footpoint longitude of the observing spacecraft. This assumes that the observing spacecraft was directly connected magnetically to the solar source region. This is almost certainly not the case, but it provides another measure of the maximum sigma. These values are given in the last column of Table 1.

Integration Time Year Start Date Hr-End Date Hr	AR Number	Location from Earth	Observing Spacecraft	^{3}He Fluence $(cm^2\ sr\ MeV/n)^{-1}$	Sigma from AR (°)	Sigma (°)
2010 Aug 23 06 - Aug 26 00	11098	N14W148	STA	109	25	15
2010 Nov 11 00 - Nov 15 00	11123	S26E08	STB	302	15	25
2011 Oct 29 00 - Oct 30 00	–	W175	STA	243	35	25
2012 Jun 27 00 - Jun 28 18	11513	N16E70	STB	333	35	35
2012 Nov 6 00 - Nov 8 12	–	W130	STA	172	25	35
2012 Dec 1 18 - Dec 4 00	11625	N13E33	STB	139	25	35
2012 Dec 9 18 - Dec 11 19	–	W178	STA	293	35	35
2010 Feb 8 12 - Feb 11 00 2010 Feb 7 24 - Feb 11 18 2010 Feb 8 12 - Feb 11 00	11045	N23W01	STB ACE STB	210 110 7	45	

Table 1: Characteristics of selected single spacecraft events. Maximum sigmas are given for analysis assuming the Gaussian is centered on the identified source location (6th column) and analysis assuming the Gaussian is centered on the location of the observing spacecraft magnetic footpoint (last column). The multi-spacecraft event of 7 February 2010 is given for comparison at the bottom of the table.

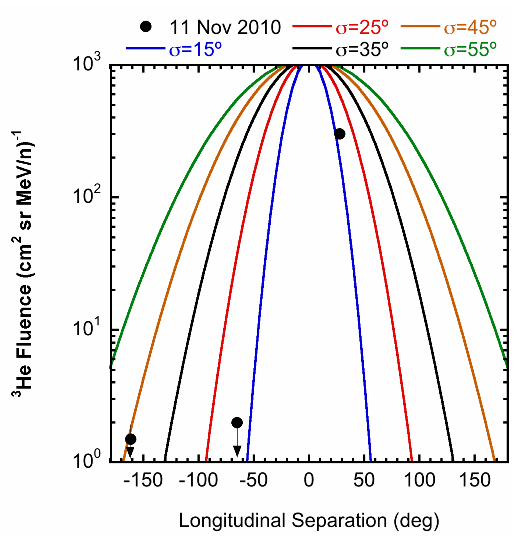

Fig. 3: ^{3}He fluences vs longitudinal separation from the flare location for the 11 November 2010 event detected by STEREO-B; upper limits are shown for ACE and STEREO-A at their respective separations. The lines show Gaussian distributions of different sigmas. Only a Gaussian with a sigma less than ~15-20° is consistent with the data.

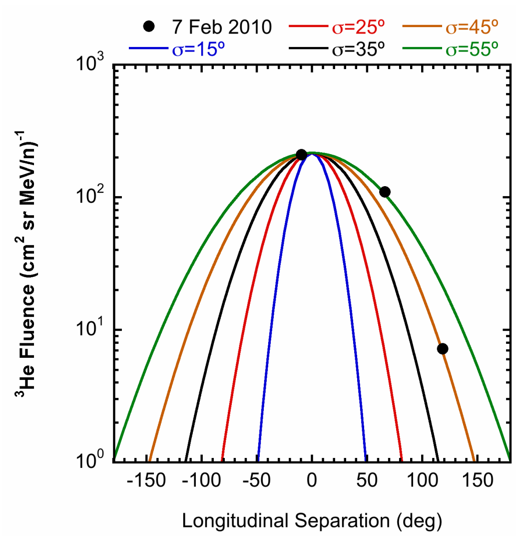

Fig. 4: Observations for the 7 February 2010 multi-spacecraft event of [2] in the same format as Figure 3. A Gaussian with a sigma of 45-55° is consistent with the data, in agreement with the fit sigma of 48° determined by Wiedenbeck, et al. [2].

3 Discussion

Figure 4 shows the same maximum sigma analysis applied to the multi-spacecraft observations for the 7 February 2010 event analyzed by Wiedenbeck, et al. [2]. The data are consistent with a maximum sigma of 45-55° in agreement with the sigma of 48° derived from a Gaussian fit by Wiedenbeck, et al. [2]. As can be seen from Table 1, all of the single-spacecraft events analyzed here suggest sigmas significantly less than this value, regardless of whether the Gaussians were centered on the location of the identified solar source or the footpoint of the observing spacecraft.

It should be noted that the modeling done by Giacalone and Jokipii [4] indicates that the center of the observed longitudinal distribution is not colocated with the solar source longitude, but rather shifted to the west. In their simulations this is largely due to corotation of the field lines and particles over the course of the event, an effect that also results in a westward skewing of the simulated longitudinal distribution of the particles such that the results were distinctly non-Gaussian. Unfortunately, due to the limitations of our current analysis neither of these effects can be accurately investigated at this time. We note that using Gaussians centered at a position 20° west of the solar source longitude does not significantly change the maximum sigmas derived for the events (within the 10° steps studied).

Another consideration that is beyond the scope of the current analysis, is the possibility that the non-observing spacecraft fluences should be examined for a time period shifted relative to that of the observing spacecraft. A significant delay was found in the onset of the ^{3}He intensities for ACE and STEREO-A in the 7 February 2010 event [2]. It is possible that modeling, such as that done by Giacalone and Jokipii [4], may provide some indication of how much of a delay would be typical for the less well-connected spacecraft. Surveying the delays present in other multi-spacecraft events may also yield some additional guidance. While these considerations will be examined in future work, it should be noted that due to the rapid fall-off of the Gaussians with longitudinal separation, typically the upper limits would need to increase by an order of magnitude or more to change the maximum sigmas reported here by more than 10°.

Given that these single-spacecraft events appear to have narrower longitudinal distributions than previously studied multi-spacecraft ^{3}He-rich events, it is natural to ask whether there are interplanetary or solar conditions that differ substantially between the multi-spacecraft and single-spacecraft events. One possible factor is the presence of CMEs, particularly prior to the event onset, that may significantly disturb the magnetic field lines from a Parker spiral configuration. In an effort to investigate this we tabulated the number of CMEs occuring in the 24 hours prior to the start of the SEP event (along with their widths and speeds) using data from http://cdaw.gsfc.nasa.gov/CME_list/; only CMEs that were measured beyond 10 solar radii were counted. The period around the 27 June 2012 event was quite active with 5 prior CMEs being observed; the 26 April 2011 and 29 October 2011 events had 2 prior CMEs; the 6 November 2012 event had 1 and the other events had none (although there is a data gap prior to the 23 August 2010 event). For comparison the 7 February 2010 event had 2 prior CMEs.

Although the number of preceding CMEs does not appear to distinguish between the narrower events we studied and the wide-longitude February event, only the 7 February 2010 event had a prior halo CME. With two exceptions, all the prior CMEs for the single-spacecraft events had widths less than 90° and the two exceptions had speeds of less than 300 km/s (as opposed to the halo CME which had a speed of 421 km/s). A closer examination of the location and propagation direction of the CMEs may prove to be useful in evaluating their effect on SEP propagation through the interplanetary medium.

Our analysis of these seven single-spacecraft ^{3}He-rich events has yielded maximum sigmas significantly smaller than that found in wide-longitude multi-spacecraft events. This shows that the longitudinal spread of the SEPs in the interplanetary medium is variable, being neither routinely as narrow as previous studies suggested (e.g., [3]) nor always as wide as found in multi-spacecraft studies (e.g., [2]). That the longitudinal distribution varies significantly from event to event suggests that the primary controling factor must be related to a mechanism that itself varies. Exactly what this is remains to be discovered.

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