Recurring \(^3\)He-rich Solar Energetic Particle Events

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Abstract: Using the SIT instrument aboard STEREO we have examined the abundance of the \(^3\)He during the ascending phase of solar cycle 24 from January 2010 through December 2012. We report on several cases when \(^3\)He-rich solar energetic particle events were successively observed on ACE and STEREO-A with delays consistent with the Carrington rotation rate. In the investigated period ACE and STEREO-A were significantly separated in the heliolongitude corresponding to solar rotation times of 5 to 10 days. We inspect STEREO-A EUV images and use the potential-field source-surface extrapolations together with in-situ magnetic field data to identify responsible solar sources. We find the \(^3\)He/\(^4\)He ratio highly variable in these events and correlated between the spacecraft for the cases with the same connection region on the Sun.

Keywords: solar energetic particles, flares, abundances, PFSS.

1 Introduction

\(^3\)He-rich solar energetic particle (SEP) events are characterized by huge enhancements of the rare isotope \(^3\)He over solar system abundances. The enrichment of the \(^3\)He is believed to be caused by selective heating mechanisms due to its unique charge to mass ratio (see e.g., review by [1]). Recently the sources of such events have been investigated with help of imaging observations [2, 3]. The sources were small flares located near open field region and showed tendency to recur [3].

There were reported a few simultaneous \(^3\)He-rich SEP events [4, 5] observed on spatially separated spacecraft (s/c). Multi-spacecraft observations of successive events have not been systematically investigated. In the present paper, we examine \(^3\)He-rich SEP events successively observed on two s/c widely separated in heliolongitude and identify cases where they are connected to the same solar active region. We use observations from the ACE and STEREO-A (STA) s/c which had a separation between 65° and 130° during the study period (January 2010-December 2012).

2 Observations

Energetic \(^3\)He observations used in this paper are from time-of-flight mass spectrometers SIT [6] on STA and ULEIS [7] on ACE. The STA s/c is in a heliocentric orbit at \(\sim 1\) AU near the ecliptic plane increasing its separation from Earth at a rate of \(\sim 22°/\)year. The ACE s/c is in an orbit around the L1 point. Since SIT is less sensitive to small \(^3\)He-rich SEP events than ULEIS we identified events on STA first and then we search for the corresponding events on ACE.

In the survey period there were 32 STA \(^3\)He-rich events found in the energy range 0.2 – 0.5 MeV/n (8 events in 2010; 12 in 2011 and 12 in 2012). In 19 cases a \(^3\)He-rich event was observed at the same energy earlier by ACE with the start time within \(\pm 2\) days of corotation delay between the two s/c. A common connection solar region was found in 12 cases, which are listed in Table 1.
Figure 1: Photospheric magnetic field with PFSS model coronal field lines at the start times of the ACE events. Shown are field lines which intersect source surface at latitudes 0° and ±7°. Red/green indicates negative/positive open field. Blue/purple diamonds mark Earth/STA footpoints on the source surface for event start times on ACE. Yellow circles mark the ACE s/c connection locations on the Sun. The open blue diamond in panel 2010-Nov-17.7 indicates Earth(ACE) position on 2010-Nov-14.6. Note that during the events the s/c footpoint moves several degrees toward the left.

Table 1: Recurring $^3$He-rich SEP events consecutively detected by ULEIS/ACE and SIT/STEREO-A.

| Year | Start time | $^3$He/$^4$He | Fe/O | $^3$He Fluence (x10$^3$) | AR |
|------|------------|----------------|------|--------------------------|----|
| 2010 | Jan 27.3   | 0.13±0.02      | 0.29±0.04 | 0.58±0.10 | 5.72±0.83 | 7.78±0.91 | 1041 |
| 2010 | Feb 8.7$^b$| 0.21±0.02      | 0.54±0.05 | 0.89±0.16 | 1.50±0.34 | 21.5±1.6  | 16.0±1.3  | 1045 |
| 2010 | Oct 17.9   | 0.46±0.04      | 1.12±0.24 | 1.27±0.23 | 2.25±1.35 | 21.0±1.6  | 4.48±0.69 | 1112 |
| 2010 | Oct 17.9   | 0.46±0.04      | 0.16±0.03 | 1.27±0.23 | 1.17±0.65 | 21.0±1.6  | 3.52±0.61 | 1112 |
| 2010 | Nov 14.6   | 0.20±0.02      | 1.24±0.16 | 1.20±0.18 | 1.00±0.43 | 26.3±1.8  | 13.8±1.2  | 1124 |
| 2010 | Nov 17.7   | 2.75±0.33      | 1.24±0.16 | 1.25±0.34 | 1.00±0.43 | 32.8±2.0  | 13.8±1.2  | 1124 |
| 2011 | Jan 27.9   | 0.08±0.01      | 0.09±0.02 | 1.15±0.18 | 4.67±2.97 | 10.7±1.1  | 1.71±0.43 | 1149 |
| 2011 | Apr 29.8   | May 6.4        | 0.02±0.01 | 3.90±0.62 | ...        | 1.43±0.70 | 0.95±0.34 | 18.5±1.4  | 1197 |
| 2011 | Jul 9.0    | Jul 16.4       | 2.35±0.13 | 3.28±0.20 | 1.31±0.20 | 1.13±0.28 | 127±4     | 105±3     | 1246 |
| 2012 | Jan 7.3    | Jan 16.0       | 1.33±0.26 | 0.82±0.22 | ...        | 1.67±1.22 | 7.15±0.92 | 2.45±0.51 | 1392 |
| 2012 | Apr 24.9   | May 2.0        | 0.11±0.01 | 0.05±0.01 | 0.99±0.11 | 0.97±0.18 | 23.4±1.7  | 7.36±0.89 | 1461 |
| 2012 | Nov 20.5   | Nov 30.9       | 6.72±0.52 | 0.80±0.27 | 0.89±0.16 | ...        | 154±4     | 1.60±0.41 | 1613 |

$^a$320–450 keV/n; fluence units - particles (cm$^2$ sr MeV/n)$^{-1}$
$^b$event discussed in [5]
Figure 2: Same as Fig. 1 but for STA events start times. Open diamond in panel 2010-Oct-24.6 indicates STA position on 2010-Oct-21.4. Yellow circles mark the STA s/c connection locations on the Sun.

Further we examine if the identified connection regions were flaring before the event. For ACE we used NOAA Solar Event Reports (http://www.swpc.noaa.gov) and for STA used SECCHI EUV observations. We searched for X-ray flares or EUV brightening in 5-8 hour interval before the event start time. The length of this interval roughly corresponds to the travel time of 0.2-0.5 MeV/n ions along the spiral with length of 1.1 AU. Using the NOAA list we found X-ray flares (B or C class) in the connected regions for 5 out of 11 ACE 3He-rich SEP events in Table 1 (Feb 8, Oct 17, Nov 14, 2010; Jan 27, 2011; Jan 7, 2012). For the rest of the ACE events the SECCHI/STA EUV 195 Å images show clear brightening in the connected regions. Note that in the STA view the ARs for ACE events were seen near the eastern solar limb. The same solar source for February 8, 2010 ACE event has been reported by another study [5]. During this event, 3He was simultaneously observed by the two STEREO s/c but without known source.

We examined full resolution SECCHI images with 5-minute cadence also for STA events. The ARs associated with Oct 21, 24; Nov 22, 2010; and Nov 30, 2012 events showed clear brightening in EUV images. Significant activity with expanding and collapsing loops was seen in the AR associated with Feb 1, 2011 event and with material ejections in AR for Feb 14, 2010 event. Only minor brightening was seen in ARs marked for the Feb 2, 2010; May 6, 2011 and Jan 16, 2012 events. Small AR 1246 at the border of the coronal hole, associated with ACE Jul 09, 2011 event, was very faint on July 16, 2011. SECCHI images showed two new regions, one emerging on the east side and other on the west side of the coronal hole. The

Figure 2 is similar to Fig. 1 but magnetic field and s/c footpoints are for STA events start times. We note that PFSS coronal model field lines are less accurate for STA events. The STA western solar hemisphere was not facing the Earth during the investigated period and thus not visible by the SOHO or SDO s/c. Notice on May 2, 2012 the Earth during the investigated period and thus not visible. Notice on May 2, 2012 the Earth during the investigated period and thus not visible.
Later one showed only little activity. $^3$He source for May 2, 2012 event is less clear. The marked AR showed no obvi- ous brightening but the AR on the south with open to ecliptic positive field lines was highly active with material eje- c tions. Although the sunspot number was lower in 2010 than in 2012, more common sources were found in 2010, when the s/c were less separated, than in 2012, when separation between the s/c markedly increased. This could be either because of the decease of the flaring in the AR or vanishing of the open ecliptic field lines during the corotation time. Anyway, identifying the events when the s/c are more sepa- rated could set up an upper limit on how long a single source may provide energetic $^3$He ions.

We found that $^3$He abundance in the events associated with the same AR does not show significant temporal changes, although other studies have not shown this. The largest difference (factor of $\sim 200$) between $^3$He enrich- ments was seen for ACE Apr 29, 2011 and STA May 6, 2011 events. This is also the case when the open field lines (of the same polarity) from several ARs were in close proxim- ity to the s/c footprint. Other larger differences (factor of 6 and 8) were found for ACE Nov 14, 2010 and STA Nov 22, 2010 events and for ACE Nov 20, 2012 and STA Nov 30, 2012 events. We note that at the beginning of the ACE Nov 14, 2010 event there were open ecliptic lines also from the southern hemisphere AR (not shown in Fig. 1). Thus the cases with the marked differences are those when multiple sources might contribute with the $^3$He.

The long lasting sources of energetic $^3$He identified in this paper tend to be regions with sunspots. It is not clear how different types/intensities of the flaring seen in these regions are related to the large event to event variability in the $^3$He enrichment.

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3 Summary

In the investigated period we have identified several $^3$He-rich events successively observed on ACE and STEREO- A when the two s/c were connected to the same solar region. Although the sunspot number was lower in 2010 than in 2012, more common sources were found in 2010, when the s/c were less separated, than in 2012, when separation between the s/c markedly increased. This could be either because of the decease of the flaring in the AR or vanishing of the open ecliptic field lines during the corotation time. Anyway, identifying the events when the s/c are more sepa- rated could set up an upper limit on how long a single source may provide energetic $^3$He ions.

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