Long-lived energetic particle source regions on the Sun

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Abstract. Discovered more than 40 years ago, impulsive solar energetic particle (SEP) events are still poorly understood. The enormous abundance enhancement of the rare \(^3\)He isotope is the most striking feature of these events, though large enhancements in heavy and ultra-heavy nuclei are also observed. Recurrent \(^3\)He-rich SEPs in impulsive events have only been observed for limited time periods, up to a few days which is typically the time that a single stationary spacecraft is magnetically connected to the source active regions on the Sun. With the launch of the two STEREO spacecraft we now have the possibility of longer connection time to solar active regions. We examined the evolution of source regions showing repeated \(^3\)He-rich SEP emissions for relatively long time periods. We found that recurrent \(^3\)He-rich SEPs in these long-lived sources occur after the emergence of magnetic flux.

1. Introduction

The acceleration of \(^3\)He-rich solar energetic particles (SEPs) and their escape into interplanetary space remains an unresolved question in solar physics. Anomalous abundances with several orders of magnitude enhanced \(^3\)He (\(\sim10^4\)) and ultra-heavies (\(\sim10^2\)) suggest a unique acceleration mechanism operating in the active regions on the Sun (see [1], for a review).

Recurrent \(^3\)He-rich SEP emissions observed by a single spacecraft during 1-2 days [2, 3, 4, 5] or 2-3 days [6] have suggested a steadier production/release of energetic ions from solar source regions [7]. Multiple spacecraft observations have recently shown that the source regions may produce recurrent SEPs for a much longer time - about a quarter of a solar rotation [8]. It remains unclear what mechanisms in such long-lived sources lead to the repeated particle emission. Is the production more stationary or rather intermittent during such long periods?

To address these questions we examine in this paper a temporal evolution of the three long-lived \(^3\)He-rich SEP source active regions (ARs). Two of them were previously reported (AR 11244, 11246) and one is newly identified (AR 11045).

2. Observations

An overview of the source ARs’ locations on the solar disk and the spacecraft ecliptic positions during the corresponding \(^3\)He-rich SEP events is shown in Figure 1. Left and middle columns
of Figure 1 show AIA [9] and EUVI [10] extreme ultraviolet (EUV) running difference images of the long-lived $^3$He-rich SEP source ARs 11244, 11246 and 11045 close to the time of events associated type III radio burst onsets. The events from ARs 11244 and 11246 were examined in detail in [8]. AR 11244 was responsible for the 2011 July 1 $^3$He-rich SEP event observed by STEREO-B and the July 7 event observed at the Earth (L1) by ACE. In both cases AR 11244 was near the west limb, at W97 or W87. Figure 1 (upper row) shows this AR near the central meridian from the Earth (SDO) and STEREO-A views. AR 11246 was responsible for the 2011 July 9 event on ACE and the July 16 event on STEREO-A. This source was located at the
Table 1. $^3$He-rich SEP events

| Start time$^a$ | Spacecraft | Type III burst | AR   | AR location$^b$ |
|---------------|------------|----------------|------|-----------------|
| 2011 Jul 1.9  | B          | Jul 1 12:36    | 11244| N14W06          |
| 2011 Jul 7.9  | ACE        | Jul 7 14:31    | 11244| N14W87          |
| 2011 Jul 9.0  | ACE        | Jul 8 16:25    | 11246| N15W45          |
| 2011 Jul 16.4 | A          | Jul 15 18:46   | 11246| N15W138         |
| 2010 Feb 7.0  | B          | Feb 6 18:53    | 11045| N21E15          |
| 2010 Feb 14.6 | A          | Feb 14 06:45   | 11045| N21W91          |

$^a$ at 275 keV nucleon$^{-1}$; nominal travel time of ions of this energy from Sun to 1 AU is about 0.3 day

$^b$ from the Earth view

coronal-hole boundary ($\sim$W45) and had a quite small size. In contrast, AR 11045 was quite sizeable and was the source of the 2010 February 6 and 7 events on STEREO-B, the February 8 event on ACE [11] and the February 14 event on STEREO-A (see Appendix A). The $^3$He increase on February 6 contained too much spillover from $^4$He to be unambiguously identified as a $^3$He-rich event [11]. However, SIT [12] on STEREO-B shows low energy Fe/O enhanced to $\sim$1 indicating a possible impulsive flare origin of this $^3$He increase. Table 1 lists $^3$He-rich SEP events and sources examined in this paper.

Figure 2 shows the evolution of the source ARs in SDO HMI [13] magnetograms (2011 July 1, July 7 and July 9 events) or in STEREO-A EUV images (2011 July 16, 2010 February 14 events). For each event a sequence of three images is shown. The first image is around the beginning of the region emergence and the third is around the particle injection time from that region. The magnetic field evolution in AR 11045 (the source of the 2010 February 6 event) has been examined in detail in [14].

AR 11244 had started to form by the emergence of a positive polarity magnetic flux in a negative polarity area at the end of 2011 June 29 (see Figure 2a), $\sim$1.5 day before the ion injection in the July 1 $^3$He-rich SEP event. The potential-field source-surface (PFSS) extrapolations indicate that open field in AR 11244 has negative polarity [8]. Another magnetic flux emergence (of negative polarity) occurred in the same AR 11244 on 2011 July 6 (see Figure 2b), $\sim$1 day before the $^3$He-rich SEP injection. The event was accompanied by multiple electron events with the first type III burst at 05:10 UT.

The creation of AR 11246 was associated with a negative polarity flux emergence in a coronal hole (of a positive polarity) on 2011 July 7 (see Figure 2c), $\sim$1 day before the ion injection. The emergence covered a small and compact region in contrast to AR 11244. In 2011 July 16 event, the source AR 11246 was out of the Earth view and therefore its evolution could be seen only in STEREO-A EUV images. Figure 2d shows a new brightening at the AR 11246 location on July 14 which may be related to further magnetic flux emergence. This occurred $\sim$1 day before the SEP injection. Note that the event was associated with several type III bursts starting at 12:40 UT on July 15.

AR 11045 emerged on 2010 February 5 with a positive polarity field into a negative polarity area [14], $\sim$1.5 day before the ion injection observed by STEREO-B. The emerging phase of this AR ended on February 8. The PFSS extrapolations along with interplanetary magnetic field (IMF) polarity suggest that ACE was connected to AR 11045 for several days at least until the AR rotated behind the limb on February 14 but no further event on ACE was observed. Li et al. [14] report another magnetic flux increase in AR 11045 on February 12 when the region was close to the west limb. STEREO-A EUV images (see Figure 2e) show a creation of a new flaring
Figure 2. (a, b, c) SDO HMI magnetograms. (d) STEREO-A EUVI 195 Å images. (e) STEREO-A EUVI 304 Å images. The ellipses mark the areas of the magnetic flux emergence (a, b, c) or new flaring activity (d, e).
area in the west edge of AR 11045, perhaps related to the same magnetic flux increase. This emergence occurred \( \sim 1.5 \) day before \(^{3}\text{He}\)-rich SEP injection observed by STEREO-A.

3. Summary and discussion
We investigated the temporal evolution of previously reported long-lasting \(^{3}\text{He}\)-rich SEP source ARs 11244 and 11246. We also identified a new long-lasting source AR 11045 and examined its evolution. We found that recurrent \(^{3}\text{He}\)-rich SEPs in the long-lived sources occur after the emergence of magnetic flux. All these ARs were newly emerging with the first particle emission occurring within \( \sim 1-2 \) days after the emergence. Interestingly, the next \(^{3}\text{He}\)-rich SEP event in the same source was associated with additional magnetic flux emergence. The EUV images or PFSS extrapolations indicate that all three sources probably emerged into pre-existing open field.

Our observations are consistent with an earlier example of particle injection in the 2002 December 12 \(^{3}\text{He}\)-rich SEP event, which occurred about 1 day after the emergence of magnetic flux in a unipolar area [5]. The authors have suggested that such a process may lead to magnetic reconnection, followed by particle acceleration on open field lines.

The presented long-lasting sources exhibited a wide range of coronal activities. For example, AR 11244 produced several cool, surge-like eruptions, as well as a number of GOES B-class X-ray flares. In contrast, AR 11246 produced only small EUV brightenings. AR 11045 was the most active region with several B-, C- and M-class flares (as well as hard X-rays) and few slow coronal mass ejections. This likely implies that there is no preferred type of \(^{3}\text{He}\)-rich SEP source. It appears that any AR can be a \(^{3}\text{He}\)-rich SEP source if there is magnetic flux emergence near the open field region.

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Appendix A.
Figure A1 shows February 14 \(^{3}\text{He}\)-rich SEP event observed by STEREO-A. The spacecraft was connected via negative polarity field lines to AR 11045 as indicated by the PFSS extrapolations (Figure A1a) along with IMF polarity. The event shows velocity dispersion (Figure A1c) and occurred during the large gradual event observed by both SOHO and STEREO-A (Figure A1b). Note that high ion counts in SIT spectrograms (Figures A1c, A1d) after the \(^{3}\text{He}\)-rich SEP event are due to interplanetary shock passage. Figure A1 indicates that L1 spacecraft were also connected to AR 11045 but ACE did not observe the same \(^{3}\text{He}\) injection. Perhaps ACE had a connection to different area in AR 11045.

References
[1] Mason G M 2007 Space Sci. Rev. 130 231
[2] Reames D V and Stone R G 1986 Astrophys. J. 308 902
[3] Mason G M, Mazur J E and Dwyer J R 1999 Astrophys. J. Lett. 525 L133
[4] Mason G M, Dwyer J R and Mazur J E 2000 Astrophys. J. Lett. 545 L157
[5] Wang Y M, Pick M and Mason G M 2006 Astrophys. J. 639 495
[6] Chen N H, Bučík R, Innes D E and Mason G M 2015 Astron. Astrophys. doi: 10.1051/0004-6361/201525618
[7] Pick M, Mason G M, Wang Y M, Tan C and Wang L 2006 Astrophys. J. 648 1247
[8] Bučík R, Innes D E, Mall U, Korth A, Mason G M and Gómez-Herrero R 2014 Astrophys. J. 786 71
Figure A1. (a) Photospheric magnetic field with PFSS model coronal field lines (red - negative and green - positive polarity) around the injection time in STEREO-A February 14 $^3$He-rich SEP event. Shown are field lines which intersect source surface at latitudes $0^\circ$ and $\pm 7^\circ$. Diamonds mark L1 and STEREO-A (STA) magnetic foot-points on the source surface. Black vertical line marks west solar limb from the Earth view. (b) SOHO (L1) and STA proton intensities. (c) SIT-A kinetic energy spectrogram of all ions. (d) SIT-A helium mass spectrogram at 0.2-0.5 MeV nucleon$^{-1}$. Shaded region marks $^3$He-rich SEP event.
[9] Lemen J R et al 2012 Sol. Phys. 275 17
[10] Howard R A et al 2008 Space Sci. Rev. 136 67
[11] Wiedenbeck M E, Mason G M, Cohen C M S, Nitta N V, Gómez-Herrero R and Haggerty D K 2013 Astrophys. J. 762 54
[12] Mason G M, Korth A, Walpole P H, Desai M I, Von Rosenvinge T T and Shuman S A 2008 Space Sci. Rev. 136 257
[13] Scherrer P H et al 2012 Sol. Phys. 275 207
[14] Li L P, Zhang J, Li T, Yang S H and Zhang Y Z 2012 Astron. Astrophys. 539 A7