OBSERVATIONS OF EUV WAVES IN \(^{3}\text{He}\)-RICH SOLAR ENERGETIC PARTICLE EVENTS

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ABSTRACT

Small \(^{3}\text{He}\)-rich solar energetic particle (SEP) events with their anomalous abundances, markedly different from the solar system, provide evidence for a unique acceleration mechanism that operates routinely near solar active regions. Although the events are sometimes accompanied by coronal mass ejections (CMEs), it is believed that mass and isotopic fractionation is produced directly in the flare sites on the Sun. We report on a large-scale extreme-ultraviolet (EUV) coronal wave observed in association with \(^{3}\text{He}\)-rich SEP events. In the two examples discussed, the observed waves were triggered by minor flares and appeared concurrently with EUV jets and type III radio bursts, but without CMEs. The energy spectra from one event are consistent with so-called class-1 (characterized by power laws) \(^{3}\text{He}\)-rich SEP events, while the other with class-2 (characterized by rounded \(^{4}\text{He}\) and Fe spectra), suggesting different acceleration mechanisms in the two. The observation of EUV waves suggests that large-scale disturbances, in addition to more commonly associated jets, may be responsible for the production of \(^{3}\text{He}\)-rich SEP events.

Key words: acceleration of particles – Sun: flares – Sun: particle emission – waves

Supporting material: animations

1. INTRODUCTION

Discovered more than 40 years ago, \(^{3}\text{He}\)-rich solar energetic particles (SEPs) are still poorly understood. The enormous abundance enhancement (up to factors of \(>10^4\)) of the rare \(^{3}\text{He}\) isotope is the most striking feature of these events, though large enhancements in heavy (Ne–Fe) and ultra-heavy nuclei are also observed (see Kocharov & Kocharov 1984; Mason 2007, for a review). Type III radio bursts with their parent low-energy electrons are firmly associated with \(^{3}\text{He}\)-rich SEP events (Reames et al. 1985; Nitta et al. 2006). Solar sources of \(^{3}\text{He}\)-rich SEPs are often accompanied by jet-like emissions in extreme-ultraviolet (EUV) or X-ray images and sometimes in white-light reaching out to distances \(>2\) solar radii \((R_{\odot})\) (Nitta et al. 2006, 2008; Wang et al. 2006). Somewhat surprisingly, an association with fast and narrow coronal mass ejections (CMEs) has been reported in some \(^{3}\text{He}\)-rich SEP events (Kahler et al. 2001; Nitta et al. 2006). CMEs with their driven shocks have been considered as a particle source for large gradual events, while \(^{3}\text{He}\)-rich SEPs are believed to be produced directly in flare sites presumably through gyroresonant wave-particle interactions (see review by Reames 2013). The CMEs associated with \(^{3}\text{He}\)-rich SEP events may be considered to be high-altitude counterparts of reconnection X-ray jets discovered by Shibata et al. (1992).

What other signatures of solar activity can be associated with \(^{3}\text{He}\)-rich SEPs? Recently Nitta et al. (2015) described the properties of a large sample (29) of \(^{3}\text{He}\)-rich events with Solar Dynamics Observatory (SDO) observations of their solar source regions. About half of the events were associated with jets and another half with wider eruptions. Four were associated with large-scale disturbances (EUV waves) and slow \((<350\ \text{km}\ \text{s}^{-1})\) CMEs. Coronal EUV waves in large gradual SEP events have been observed for almost two decades (Torsti et al. 1999). Some authors have recently attempted to explain SEP events observed at widely separate longitudes in terms of EUV waves (e.g., Rouillard et al. 2012; Park et al. 2013; Lario et al. 2014). At the outset of the eruption they appear to trace the progress of the shock responsible for particle acceleration. However, the association of EUV waves with \(^{3}\text{He}\)-rich SEP events has seldom been discussed (Wiedenbeck et al. 2013; Nitta et al. 2015).

In this paper, we report on two \(^{3}\text{He}\)-rich SEP events clearly associated with coronal EUV waves. The observations were made during a period of low solar activity in early 2010. We examine the relationship of the EUV waves to the accompanying energetic particles, including a detailed analysis of the wave fronts. It appears that the wave properties may be correlated with the observed ion spectra. These observations of SEP events and EUV waves are presented in Section 2, and we discuss their implications in Section 3.

2. OBSERVATIONS

The two \(^{3}\text{He}\)-rich SEP events reported in this paper were identified using observations from the time-of-flight mass spectrometers Ultra Low Energy Isotope Spectrometer (ULEIS; Mason et al. 1998) on the Advanced Composition Explorer (ACE) and the Suprathermal Ion Telescope (SIT; Mason et al. 2008) on the Solar Terrestrial Relations Observatory AHEAD spacecraft (STEREO-A). The responsible solar sources were examined in full-Sun images from the EUV imager (Howard et al. 2008) on STEREO. ACE is in an orbit around the L1 point; STEREO-A is in a heliocentric orbit at \(\sim 1\) AU near the ecliptic plane moving faster than Earth at a rate of \(\sim 22^\circ\ \text{yr}^{-1}\).

2.1. \(^{3}\text{He}\)-rich SEP Events

Figure 1 shows two \(^{3}\text{He}\)-rich SEP events, one observed by ACE on 2010 January 26 (left panels) and another by STEREO-
A on 2010 February 2 (right). These are among the first $^3$He-rich SEP events detected after the unusually low solar minimum between solar cycles 23 and 24 (the February 2 event is also identified in Wiedenbeck et al. 2013). Both events were accompanied by energetic electron enhancements observed by EPAM/ACE (Gold et al. 1998) or SEPT/STEREO-A (Müller-Mellin et al. 2008), as shown in Figure 1(a). The approximate onset of the EPAM electron event on January 26 is at 17:25 UT (45 keV). The onset of the SEPT electron event on February 2 is quite uncertain; the main increase starts around 12:00 UT (50 keV), but it was preceded by another minor event. Figure 1(b) shows individual ions in the helium mass range at 0.4–10 MeV nucleon$^{-1}$ for ULEIS/ACE and at 0.25–0.90 MeV nucleon$^{-1}$ for SIT/STEREO-A. The $^3$He track is clearly separated in ULEIS data. An examination of SIT mass histograms in the February 2 event confirms a clear $^3$He peak within the helium range (see Figure 2(b)). The January 26 event has a clear dispersive onset, where higher energy ions arrived earlier than lower energy ones, as shown by the triangular pattern in the inverted ion-speed time spectrogram in Figure 1(c). The February 2 event could also have been dispersive, but it is possible that a magnetic-cloud like structure may have reduced the intensity of energetic ions (e.g., Cane & Lario 2006). The interplanetary magnetic field (IMF) data from the MAG/ACE instrument (Acuña et al. 2008) shows a smooth rotation of the magnetic field vector during 14–20 UT (see Figure 1(c)). The 320–450 keV nucleon$^{-1}$ $^3$He/$^4$He ratio is 0.13 for January 26 and 0.41 for February 2 event. The Fe/O ratio is $\sim$0.6 in both events; somewhat smaller than the average value in $^3$He-rich flares (see $\sim$0.95 at 385 keV nucleon$^{-1}$ in Mason et al. 2004).

The January 26 event was associated with a B3.2 GOES X-ray flare in active region (AR) 1042 (N20°W75°) with a start time at 17:01 UT (Solar Events List$^6$). Close to the time of the flare onset, a strong type III radio burst was observed by WAVES/WIND (Bougeret et al. 1995; see Figure 1(d)). The estimated ion solar release time from extrapolation of ULEIS spectrogram data to the zero propagation time is around the type III burst onset, though uncertainty arising from this technique has been reported to be ±45 minutes (Mason et al. 2000). Less clear is the ion release time in the February 2 event. The event (from different AR; see Section 2.3) may be related to the preceding main electron increase and associated type III burst at 11:42 UT measured by WAVES/STEREO-A.

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$^6$ www.swpc.noaa.gov
Bougeret et al. 2008; other type III bursts preceding the event occurred at 10:24 and 07:04 UT (see Figure 1(d)). The burst at 07:04 UT is also significant, extending to both high and low frequencies, and may be associated with an observed minor electron intensity increase. Hereafter, we focus on the type III burst at 11:42 UT because it was associated with the main electron event. The Solar Radio Bursts Report7 includes type III bursts at 17:03 on January 26 in the frequency range of 25–144 MHz (Sagamore Hill) and type III bursts at 07:04 on February 2 in the 20–130 MHz (Culgoora) range. The type III burst at 11:42 UT on February 2 extended into the range of 20–70 MHz8 (Nançay Decameter array). No metric type II radio bursts were observed in these two events.

Figure 2. Energy spectra for January 26 (a) and February 2 (b) 3He-rich SEP events. Gray shaded histogram is for the February 2 event. Red histogram is for corotating interaction region events (2010 May–June) to compare SIT observations with no 3He mass peak.

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Figure 2(a) shows event averaged fluence spectra for January 26, and Figure 2(b) shows the spectra for the February 2 3He-rich SEP event. The January 26 spectra for 3He, 4He, O, and Fe have similar power laws. They are reminiscent of class-1 event spectra where major species exhibit similar power laws or broken power laws with 3He often showing stronger hardening below ∼1 MeV nucleon−1 (Mason et al. 2000, 2002). In the February 2 event, 4He and O have similar power laws, but the 3He and Fe spectra are distinctly flatter, leading to a larger variation of 3He/4He and Fe/O with energy than in the January 26 event. The February 2 event spectra are similar to the class-2 event spectra, characterized by curved 3He and Fe spectra toward low energies with 3He rollovers in the range of ∼100–600 keV nucleon−1 and Fe rollovers below ∼100 keV nucleon−1 (Mason et al. 2000). Certainly, the spectral shapes in these two events are not very representative of class-1 or class-2 events. There are fluctuations at several spectral points making it somewhat difficult to categorize the January 26 event solely by its 3He shape. Note, the median value of 3He/4He ratio of class-1 events (∼0.12 at 385 keV nucleon−1 in Mason et al. 2002) is strikingly similar to 3He/4He ratio in the January 26 event.

2.2. EUV Wave—January 26 Event

During the investigated events ACE and STEREO-A were angularly separated by 65°, allowing the near-west limb regions from ACE to be observed in a more direct view by STEREO-A. We emphasize that such a constellation enables a completely new insight on 3He-rich sources, not available in earlier investigations. Figure 3 (left) shows the EUV 195 Å image of AR 1042 near the central meridian in the STEREO-A view. Running difference images in Figure 3 (right) show jet-like emissions at 17:00–17:05 UT in the eastern foot-point of a series of small magnetic loops. The observed temporal coincidence between the EUV jet in AR 1042 and the type III burst indicates that the AR contains open field allowing particles to escape.

A large-scale wave was observed emanating from AR 1042, the 3He-rich SEP source, as demonstrated in running difference images in Figure 3. The wave was clearly seen, even in direct EUV images (see the animation of Figure 3 (left)). The launch time of the wave temporarily coincides with the EUV jet. A bright wave front was clearly seen at 17:05 UT (∼4 minutes after the X-ray flare and 2 minutes after the type III burst), but a weaker arc-shaped dimming, probably associated with the wave, was already seen at the type III burst onset. The wave front propagated southward toward the equator and nominal spacecraft foot-point based on the Parker spiral model. The nominal foot-point location was not reached before 17:15 UT, but the electron, and likely also the ion, release was associated with the jet, type III burst and the wave-launch that occurred

\[\text{ftp.ngdc.noaa.gov}\]
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26–Jan–2010 17:03:00 UT STEREO–A 195Å

Figure 3. (Left) STEREO–A 195 Å EUV image of the solar disk on 2010 January 26 17:03 UT. (Right) Six panels—2.5-minute (except for 17:10:30, which is 5-minute) running difference images of the area around AR 1042 marked by red square in the direct image. Red crosses indicate nominal foot-point of IMF line connecting to L1. Two red curves, passing through the AR (panel 17:10:30), indicate a 70° arc sector on the solar sphere where the EUV intensity profiles in Figure 5 were determined. The red curve along the wave front outlines an arc centered on the AR.

(An animation of this figure is available.)

The nose of the wave front traveled 15° in latitude between 17:03 and 17:13 UT, which corresponds roughly to 300 km s\(^{-1}\). This is within the range (200–400 km s\(^{-1}\)) of typical EUV wave speeds (Thompson & Myers 2009) and is comparable with quiet-Sun fast magnetosonic speeds. Previous observations have shown that EUV waves can be faster in the early stage and may even be shocks (e.g., Warmuth & Mann 2011). Indeed, newer high-cadence observations, capable of capturing the initial phases of the wave evolution, indicate much higher speeds (~600 km s\(^{-1}\); Nitta et al. 2013) implying that these waves may steepen to shocks quite frequently. EUV wave shocks directly observed as dome-like enhancements propagating ahead of a CME have been reported in some recent investigations (Veronig et al. 2010; Kozarev et al. 2011; Ma et al. 2011).

The EUV image of the Sun’s disk in Figure 3 reveals quite uniform coronal structure with the only other AR located far away, near the southeast solar limb and a coronal hole at the south-pole. This likely enabled undisturbed wave propagation and therefore its easier observation. Note that ARs/coronal holes in the paths of the waves usually cause them to fade/reflect (e.g., Thompson et al. 1999). The fact that AR 1042 is quite isolated with no simultaneous activity observed in other regions also allowed a more straightforward identification of the \(^3\)He-rich SEP source. Note that many \(^3\)He-rich SEP events have been left without identified solar sources, for example, 40% of 117 events by Nitta et al. (2006).

The driver of EUV waves has often been associated with CMEs, but in this event there was no CME. Any CME associated with January 26 event would be best visible in a coronograph from the Earth view because of the source location near the western limb. The SOHO LASCO C2 observations, covering the range 1.5–6 \(R_\odot\), show a narrow stream at 17:54, 18:06, and 18:30 UT at the near-equatorial region on the west. In the SOHO LASCO CME catalog\(^9\) this brief eruption was classified as a very poor event. No eruption was seen from 1.4 to 4 \(R_\odot\) in STEREO–A COR–1 5-minute running difference images.\(^10\) Also the STEREO COR–1 preliminary list\(^11\) indicates no associated CME.

2.3. EUV Wave—February 2 Event

Figure 4 (left) shows the STEREO–A EUV 195 Å image of the solar source AR for the February 2 \(^3\)He-rich SEP event, located at N20°W65° from STEREO–A, which was 65° west of the Sun–Earth line. Running difference images in Figure 4 (right) show a jet at 11:45 UT, temporally coincident with a type III burst shown in Figure 1(d). Similar to the previous event, the jet was emitted from the Sun’s surface at the eastern foot-point of a series of small-scale loops. The AR emerged on 2010 January 30 when it was at the west limb as seen from the Earth. The running difference images in Figure 4 show a bright wave front emitted from the AR around the time of the jet and propagating in the southeast direction. The wave reached STEREO–A nominal foot-point around 12 UT, but the electron (and likely the ion also) release occurred earlier at 11:45 UT in association with the jet and the type III radio burst. The wave front in the February 2 event appears to be more diffuse (see wave fronts 12–13 minutes after type III burst onsets in both events at 17:15 and 11:55 UT) and less bright than in the January 26 event (see wave fronts 7–8 minutes after type III burst onsets in both events at 17:10 and 11:50 UT). The projection effects in the February 2 event probably play a minor role as the wave propagates toward the central meridian where these effects are less dominant. Because of the diffuse fronts in

\(^9\) cdaw.gsfc.nasa.gov/CME_list
\(^10\) cdaw.gsfc.nasa.gov/stereo/daily_movies
\(^11\) cor1.gsfc.nasa.gov/catalog
the February 2 event it is more difficult to measure the wave speed. A rough estimate is \( \gtrsim 200 \text{ km s}^{-1} \) between 11:45 and 12:00 UT where the wave front traveled 15° in the latitude. In direct EUV images the wave was not so clearly seen (see animation of Figure 4 (left)) as in the previous event. Note that in the February 2 event, STEREO-A provides only 5-minute cadence images while in January 26 event the cadence is 2.5 minutes. Thus, insufficient temporal resolution may be one reason why these waves were not noticed in earlier \(^{3}\text{He}\) SEP investigations. The above-mentioned projection effects due to western location of \(^{3}\text{He}\)sources may also add to the difficulty in an identification of the associated waves. The less intense type III burst at 10:25 UT (see Figure 1 (d)) was also associated with a jet and a coronal wave, but these were less significant than in the 11:42 UT type III burst. The type III at 07:04 UT also coincided with EUV brightening in the same AR, but no wave was observed. The STEREO-A COR-1 running difference images showed from 12:15 UT onward a small bright feature moving outward toward the west. This weak outflow was not marked in the COR-1 Preliminary CME List.

2.4. EUV Wave Profiles

In addition to a visual inspection as given in the previous sections, we also provide a quantitative analysis of the wave fronts. Figure 5 shows the evolution of the wave front profiles within 12 and 13 minutes after the associated type III radio bursts in the January 26 and February 2 events, respectively. A similar approach where the intensity ratios are derived along the propagating fronts is presented in earlier studies (e.g., Veronig et al. 2010). The figure reveals that the amplitudes of the intensity ratio and their temporal fluctuations are larger for the January 26 wave. The temporal behavior of the trailing front edges suggests that the January 26 wave was likely accelerating while the February 2 wave was moving with more uniform speed. These profiles also indicate lower speed for the February 2 wave.

3. DISCUSSION AND SUMMARY

This paper examines a new solar phenomenon observed in association with \(^{3}\text{He}\) SEPs. We present two events, where in addition to EUV jets, \(^{3}\text{He}\) source ARs simultaneously launched a coronal EUV wave. The waves were initiated by minor flares and not linked to CMEs. The EUV waves have been considered to be closely related to CMEs (Biesecker et al. 2002), though recent investigations (Nitta et al. 2013) indicate that the association is not so strong.

The EUV waves may be a more common feature in \(^{3}\text{He}\) SEP events than previously thought. Wiedenbeck et al. (2013) noticed large-scale disturbances in the source region of the \textit{STEREO-B} 2010 February 7 and \textit{ACE} February 8 \(^{3}\text{He}\)-rich SEP events. They suggested that EUV waves could be responsible for a sympathetic flaring in a region far from the nominal connection and thus contributing to a wide particle longitude distribution. In a parallel study, Nitta et al. (2015) reported large-scale propagating fronts in a few \(^{3}\text{He}\)-rich SEP events on \textit{ACE} by also examining active periods of a current solar cycle. Note that some other \(^{3}\text{He}\)-rich SEP events like 2008 November 4 on \textit{ACE} (Mason et al. 2009) or 2011 July 1 on \textit{STEREO-B} (Bucík et al. 2014) are also associated with EUV waves (not mentioned in original studies). Their sources are well visible near the central meridian similarly to the 2010 January 26 event.

Coronal jets, a signature of magnetic reconnection between magnetic loops and overlying open field (Shibata et al. 1992),
create turbulence for $^3$He-rich SEP acceleration (e.g., Miller 1998; Petrosian 2012). Nearly all models of $^3$He-rich SEPs require some kind of two-stage processes. For example, electrons, accelerated by cascading turbulence, excite plasma waves (Miller 1998) capable of gyrosorenton interaction with ambient $^3$He (Temerin & Roth 1992). An alternative to turbulence is the reconnection-exhaust ion heating followed by an interaction with multiple magnetic islands (e.g., Drake & Swisdak 2012). The two spectral classes of $^3$He-rich SEPs is a relatively new feature, and have not yet been adequately explained. It has been suggested that class-2 events represent the basic mechanism of $^3$He enrichment and that class-1 events explain. It has been suggested that class-2 events represent relatively new feature, and have not yet been adequately explained. In this example the wave might have been capable of modifying the original curved spectra created by turbulence or by the pick-up mechanism in the reconnection exhausts.

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\text{Figur} \text{e 5. Average EUV intensit} \text{y-ratio profiles for the January 26 (red curve) and February 2 (blue curve) wave fronts at three different times. The average ratios were determined in a 70° annular sectors with radial width 15 Mm and center in the source AR. The 70° arc sectors were placed on the brightest portion of the wave fronts (see Figures 3 and 4).}
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\begin{figure}[h]
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\includegraphics[width=\textwidth]{figure5.png}
\caption{Average EUV intensity-ratio profiles for the January 26 (red curve) and February 2 (blue curve) wave fronts at three different times. The average ratios were determined in a 70° annular sectors with radial width 15 Mm and center in the source AR. The 70° arc sectors were placed on the brightest portion of the wave fronts (see Figures 3 and 4).}
\end{figure}

Biesecker et al. (2002) noted that EUV waves with bright, sharp fronts may indicate shocks. In the second event, where the wave front was less bright and perhaps slower, the spectral forms were consistent with the class-2 events, suggesting that the influence of the wave was minor. The energy spectra of $^3$He and $^4$He in the February 2 event are quite similar to spectra in the class-2 event on 1999 September 30 (Mason et al. 2000), which were excellently fitted by stochastic acceleration (Figure 9 in Liu et al. 2006). We need to examine more events in order to evaluate the relevance of EUV waves on the two class spectra of $^3$He-rich SEPs. The two examples presented here also raise the question whether EUV waves themselves (even not steepened into the shocks) may generate or enhance turbulence required for $^3$He-rich SEP acceleration models.

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