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Impulsive Solar Energetic Particle Events: Extreme-Ultraviolet Waves and Jets

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Impulsive solar energetic particle (ISEP) events show peculiar elemental composition, with enhanced ^{3}He and heavy-ion abundances, markedly different from our Solar System composition. Furthermore, the events are characterized by a wide variety of energy spectral shapes from power laws to rounded spectra toward the low energies. Solar sources of the events have been firmly associated with coronal jets. Surprisingly, new observations have shown that events are often accompanied by so-called extreme-ultraviolet (EUV) coronal waves–a large-scale phenomenon compared to jets. This paper outlines the current understanding of the linkage of EUV waves with jets and energetic ions in ISEP events.

Keywords: solar energetic particles, element abundances, EUV waves, shock waves, solar jets, CMEs, flares

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1 INTRODUCTION

Extreme-ultraviolet (EUV) waves appear as large-scale expanding disturbances in the corona. Since their discovery, there has been a long debate (e.g., Patsourakos and Vourlidas, 2012; Liu and Ofman, 2014) whether they are true waves or just a magnetic field restructuring caused by associated coronal mass ejections (CMEs). Now, there is increasing evidence that they are true magnetosonic waves (see Warmuth, 2015, for a review). The EUV waves are regularly observed in CME-driven shock gradual solar energetic particle (GSEP) events (e.g., Torsti et al., 1999; Park et al., 2013; Lario et al., 2014), usually accompanied by large GOES X-ray (1–8 Å) flares (M-, X-class).

Recently, with help of improved imaging resolution from Solar Terrestrial Relations Observatory (STEREO) and Solar Dynamics Observatory (SDO) that provide a full-disk view of the Sun from different observing angles, there have been reported EUV waves in many impulsive solar energetic particle (ISEP) events (Wiedenbeck et al., 2013; Bučík et al., 2015, 2016a; Nitta et al., 2015; Cohen et al., 2021). Though these waves had a smaller spatial scale and were fainter than those in GSEP events, their observations in ISEP events, previously associated with compact flare signatures, were surprising. In this paper, we review the possible effects of the EUV waves on energetic ions in ISEP events and their relation to jets.

2 ISEP EVENTS: KEY FEATURES

ISEP events show tremendous (up to a factor of 10^4) enhancements of rare ^{3}He nuclide above the coronal composition (Kocharov and Kocharov, 1984; Mason, 2007; Reames, 2013, 2018). It is why these events are also called ^{3}He-rich. Heavy (^{20}Ne–^{56}Fe) and ultra-heavy ions (mass > 70 AMU; e.g., ^{207}Pb) are enhanced by a factor of 3–10 and > 100, respectively, independently of the amount of ^{3}He enhancement (Mason et al., 1986; Reames et al., 1994). It has been interpreted as evidence that

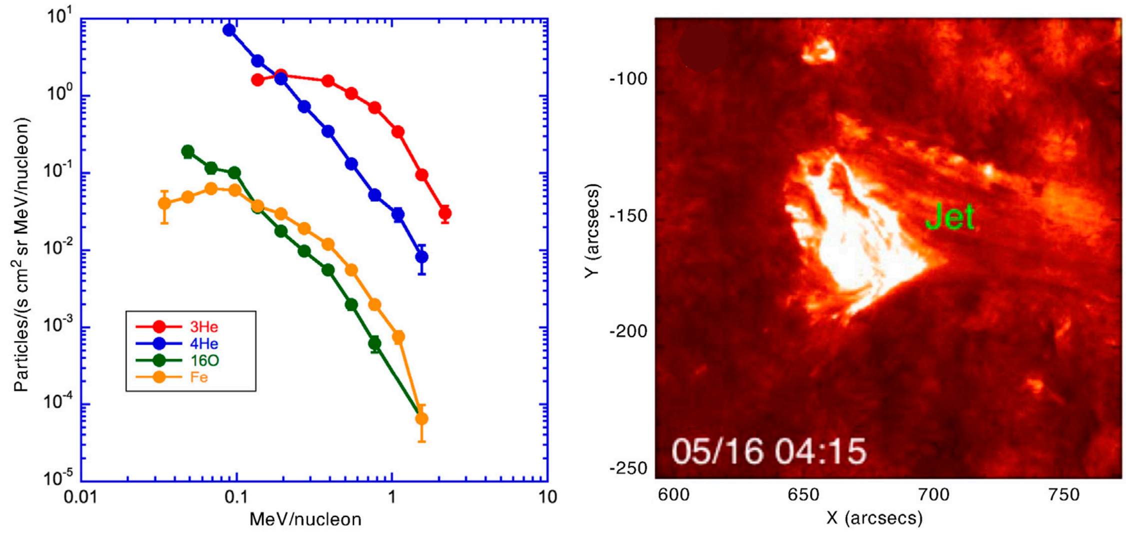

FIGURE 1 | The 2014 May 16 ISEP event. Left: Advanced Composition Explorer (ACE) ULEIS energy spectra for selected ion species. The ^{3}He and Fe spectra are rounded, the ^{4}He and O show power law shape. Adapted from Nitta et al. (2015). © AAS. Reproduced with permission. The ^{3}He/^{4}He ~14.9 over the energy range 0.5–2.0 MeV/nucleon is extremely high. The ratio is a factor of ~4 × 10^4 higher than the solar wind value. The Fe/O at 0.385 MeV/nucleon is ~2.1. The ^{28}Si and ^{32}S had also curved spectra in this event (Mason et al., 2016). Right: SDO AIA 304 Å direct image of the event solar source showing a jet eruption. Adapted from Mason et al. (2016). © AAS. Reproduced with permission. No X-ray flare was detected in this event.

different mechanisms are involved in the acceleration of the ^{3}He and the heavy ions. In a typical ISEP event, the abundances of H, ^{4}He, ^{12}C, ^{14}N, ^{16}O are unenhanced. The enhancement of heavier ions increases monotonically with their mass.

In addition to unusual abundances, these events show a rich variation of energy spectral shapes. Most events can be divided into two distinct groups: the class-1 events where all elements show similar power laws or broken power laws, and class-2 events with ^{3}He and Fe spectra curved toward low energies where H and intermediate species such as ^{4}He or O have spectra close to power law shape (Mason et al., 2000; Mason et al., 2002; Mason et al., 2016; Nitta et al., 2015; Bučík et al., 2016b). It has been suggested that rounded spectra arise from a primary mechanism of ^{3}He (Fe) enrichment, and power laws involve a further stage of acceleration by a shock wave (Mason et al., 2000; Mason et al., 2002). Note, however, that type II radio bursts produced by shock acceleration of electrons in the corona are not characteristics of ISEP events. In contrast, these events show a high (> 95%) association with type III radio bursts (e.g., Reames and Stone, 1986; Nitta et al., 2006; Wang et al., 2012), the emission generated by outward streaming ~10–100 keV electron beams. The interplanetary propagation has not been thought to dominate the spectral shapes of ^{3}He-rich SEPs though for class-1 events with spectra of similar forms for all elements, this possibility cannot be ruled out (e.g., Mason et al., 2002).

It is commonly accepted that unusual enrichments of ^{3}He-rich SEPs result from a unique acceleration mechanism associated with magnetic reconnection in solar flare sites. The models of ^{3}He acceleration involve ion-cyclotron resonance with plasma waves generated near the ^{3}He frequency (e.g., Temerin and Roth, 1992; Liu et al., 2006). Models of heavy-ion acceleration involve resonant interaction with cascading Alfvén waves (e.g., Miller, 1998) or ion scattering on reconnecting magnetic islands (Drake et al., 2009).

3 ISEP EVENTS: JETS

Source flares of ^{3}He-rich SEPs often show a jet-like shape in EUV and X-ray images (Nitta et al., 2006; Nitta et al., 2008, 2015; Wang et al., 2006; Bučík, 2020; Wiedenbeck et al., 2020) that is sometimes observed in coronagraphs as a narrow CME (Kahler et al., 2001; Wang et al., 2006, 2012). Observation of jets in ISEP sources is believed to be a signature of ion acceleration via magnetic reconnection involving field lines open to interplanetary space (Reames, 2002; Wang et al., 2006). Several events did not show jets but rather some amorphous brightening that has been attributed to instrument resolution and projection effects (Wang et al., 2006). The events are accompanied by small X-ray flares, typically B- or C-class. **Figure 1** shows the energy spectra of a class-2 ISEP event and a jet that was the event source.

A concept of two basic populations of ISEP events have been suggested: SEP1 – pure ISEP events from magnetic reconnection in solar jets and SEP2 – a mix of SEP1 from jets and ambient population, reaccelerated by shocks driven by the same jets (Reames, 2020, 2021b,a). It was primarily motivated by measurements of enhanced H abundance in ISEP events with fast narrow CMEs (e.g., Kahler et al., 2001). Recently, an excess in H has been reported for one ISEP event associated with a narrow (18°) 450 km/s CME (Cohen et al., 2021). Bronarska et al. (2018) speculated that small-width shocks associated with fast and narrow CMEs can contribute to the generation of ISEP events. The authors reported 24 very narrow (< 20°) and fast (median 724 km/s) CMEs where most (20) of them were associated with

^{3}He-rich SEPs. Wang et al. (2012), in their extensive statistical study, reported a CME median speed of 496 km/s with median width of 47° in 624 electron ^{3}He-rich SEP events. Wang et al. (2016) reported ~600–1,100 km/s CMEs with width $< 60°$ in ten electron ^{3}He-rich events. These works show that fast jet-like CMEs are not uncommon in ISEP events.

4 ISEP EVENTS: EXTREME-ULTRAVIOLET WAVES

4.1 Rate of Occurrence

When the association of ^{3}He-rich SEP events with jets became relatively well established, the reported occurrence of the EUV waves in solar sources of ^{3}He-rich SEPs (Wiedenbeck et al., 2013; Nitta et al., 2015; Bučík et al., 2015, 2016a) was surprising. More than half (20 of 32) of ^{3}He-rich events during solar minimum conditions in 2007–2010 were accompanied by EUV waves, and the remaining events were associated with jets or brightenings (Bučík et al., 2016a). Half of the 26 examined ^{3}He-rich events in 2010–2014 were accompanied by jets, four events by EUV waves, and the remaining events by an eruption showing larger angular expansion than a jet (Nitta et al., 2015). A discrepancy in the number of the observed EUV waves can be due to the event selection criteria and subjectivity in the classification of the flare shape. Bučík et al. (2016a) selected all events in the examined period, also, the events near the detection threshold, while Nitta et al. (2015) selected events with a clear ^{3}He injection or with clear ^{3}He presence preceded by > 40 keV electron event. We note that the eruptions associated with the 2010 October 17 and 2012 May 14 ISEP events in the study of Nitta et al. (2015) are marked by Bučík et al. (2016a) and Shen et al. (2018a) as EUV waves, respectively. Cohen et al. (2021) identified three ISEP events at ~0.3–0.5 au where one was associated with the jet and the other two with signatures of EUV waves.

4.2 Delays

The EUV waves were seen to propagate toward the spacecraft magnetic foot-point on the Sun, wherein more than half of wave fronts crossed the foot-point (Bučík et al., 2016a). The crossings were observed between 5 and 40 min after type III burst onset. Interestingly, ion delayed injections around 60 min after type III radio bursts were reported by Wang et al. (2016). Ho et al. (2003) found ion delays of > 40 min after ~45 keV electron release times in some ^{3}He-rich SEP events. These delays have been suggested to be due to particle scattering or the CME shock acceleration (Ho et al., 2003; Wang et al., 2016). The reported delays could also be related to the travel time of the EUV waves from the ^{3}He-rich SEP source to the spacecraft magnetic foot-point. However, no timing studies involving EUV waves and ion arrival times have been performed for ISEP events. The average uncertainties (±45 min; e.g., Mason et al., 2000) in the estimation of the < 1 MeV/nucleon ion release time on the Sun are higher than the reported travel time of the EUV wave from the source to the spacecraft magnetic foot-point.

4.3 Energy Spectra

The wave kinematics has not been systematically investigated in ISEP events. The EUV wave expansion in two ISEP events was examined by Bučík et al. (2015). The authors reported the EUV wave front propagation speed of ~300 km/s which is comparable to the typical EUV wave speed (~200–400 km/s; Thompson and Myers, 2009). The energy spectra in one event were typical of class-1 events where the associated wave showed a bright and sharp front. It has been suggested that the EUV waves with bright and sharp fronts may indicate shocks (Biesecker et al., 2002). The energy spectra in the other event were typical of class-2 events where the wave showed a blurred and less bright front. Both these events also showed a jet in the source active region. The energy spectra for the ISEP event associated with a coronal wave are shown in **Figure 2** (Left). **Figure 2** (Right) displays the event-associated EUV wave, ~8 min after type III radio burst or X-ray flare start time. The sharp wave front was seen later in the event. For four ISEP events reported in Bučík et al. (2016a), the wave speed (~260–520 km/s) was determined in earlier works (Warmuth and Mann, 2011; Nitta et al., 2013, 2014). All four events had class-1 energy spectra. The EUV wave speed of ~600 km/s for the 2011 January 27 ISEP event in Nitta et al. (2015) was reported by Muhr et al. (2014). The event had class-1 energy spectra. Nitta et al. (2013) reported a EUV wave with a speed of ~570 km/s in the 2011 February 18 ISEP event (Bučík et al., 2018) that was also associated with a jet. The event showed a double power law spectrum for ^{3}He at ~0.1–15 MeV/nucleon. The EUV wave speed in the ISEP event on 2012 May 14, mentioned in **Section 4.1**, was ~650 km/s (Shen et al., 2018a). The event showed class-1 spectra.

Table 1 shows characteristics of the ISEP events with reported EUV wave speed. Column 1 indicates the event number, column 2 the ISEP event start date, column 3 GOES X-ray flare class. Columns 4 and 5 give ^{3}He/^{4}He and Fe/O ratios, respectively. Column 6 provides the EUV wave speed. The last column indicates references where the events and speeds were reported. We can examine a correlation between elemental ratios, as shown in **Table 1**, and the EUV wave speed when more ISEP events with the estimated speed are available. Also, a correlation between the power law index and wave speed can be explored. It may help to understand the significance of EUV waves in ISEP events.

We see a tendency for ISEP events with jets only to have rounded ^{3}He and Fe spectra toward low energies and for events with coronal waves to have power law spectra (Nitta et al., 2015; Bučík et al., 2016b). Thus, EUV waves may be related to some mechanism that modifies rounded spectra. Furthermore, Cohen et al. (2021) have reported somewhat harder H and ^{4}He power law spectra in the two ISEP events with EUV wave than in the event with jet. Though the shock radio signature is not measured in ISEP events, it does not rule out that perhaps weak shocks that do not manifest as type II bursts can be formed in the flare site and re-accelerate ^{3}He-rich SEPs. It has been demonstrated with new observations (Warmuth and Mann, 2011; Nitta et al., 2013) that EUV waves at the early stages can be faster than the quiet-Sun fast magnetosonic speed (~300 km/s; e.g., Wang, 2000), implying that they can be shocks (Warmuth and Mann, 2011).

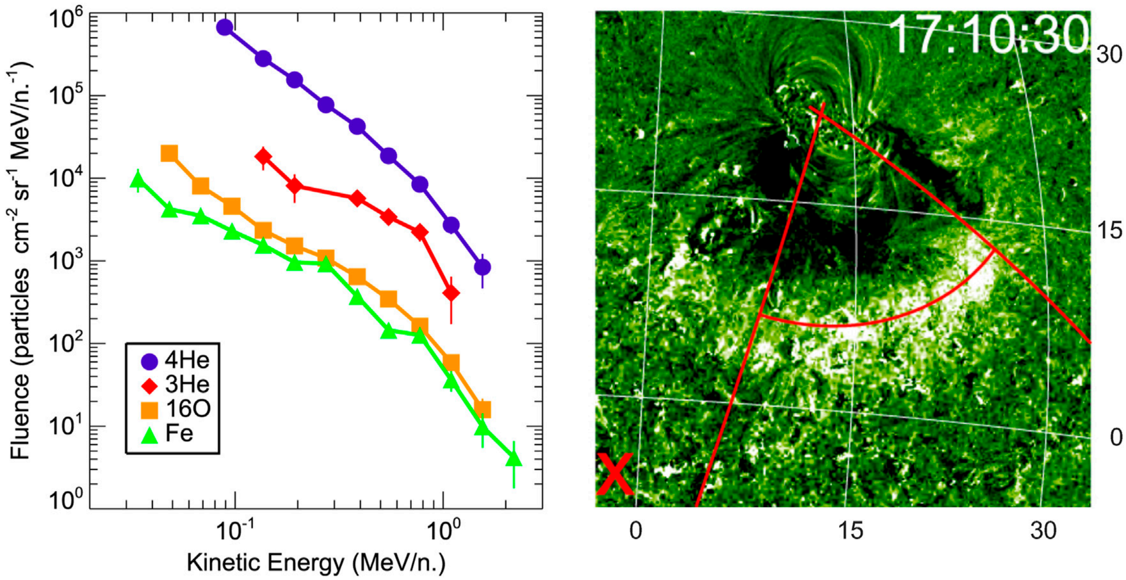

FIGURE 2 | The 2010 January 26 ISEP event. Left: ACE ULEIS energy spectra for selected ion species. The ^{4}He, O, and Fe spectra show power law form; the ^{3}He spectrum is unambiguous. Adapted from Bučík et al. (2015). The ^{3}He/^{4}He and Fe/O at 0.385 MeV/nucleon are ~0.13 and ~0.6, respectively. The ^{3}He/^{4}He is consistent with the median value of 0.385 MeV/nucleon ^{3}He/^{4}He ~0.12 in class-1 events. The Fe/O is somewhat lower than the typical value in ISEP events (~0.95 at 0.385 MeV/nucleon; Mason et al., 2004). Right: STEREO-A EUVI 195 Å 5-min running difference image of the event solar source showing a coronal wave. Adapted from Bučík et al. (2015). Two red curves, passing through the source active region (AR), outline the propagation sector where the wave speed was determined. The red curve along the wave front outlines an arc centered on the AR. The red cross marks the ACE magnetic foot-point. The B-class X-ray flare was measured in the event.

TABLE 1 | The ISEP events with reported EUV wave speed.

	ISEP event	Flare	^{3}He/^{4}He	Fe/O	Wave speed	References
	Start Date	Class			(km/s)	
1	2007 May 23	B3.9	0.01[a]	2.30[a]	322	Event in 1; Speed from 2
2	2008 Nov 4	C1.0	0.05[a]	1.45[a]	260	Event in 1; Speed from 2
3	2009 Dec 22	C7.2	1.55[a]	1.16[a]	403 (521)	Event in 1; Speed from 2 (3)
4	2010 Jan 26	B3.2	0.13[a]	0.60[a]	300	Event in 4; Speed from 4
5	2010 Feb 2	...	0.46[a]	0.60[a]	≳200	Event in 4; Speed from 4
6	2010 Jun 12	M2.0	0.02[a]	0.94[a]	487 (386)	Event in 1; Speed from 3 (5)
7	2011 Jan 27	B6.6	0.08[b]	1.13[a]	610	Event in 6; Speed from 7
8	2011 Feb 18	C1.1	0.12[c]	1.46[c]	571	Event in 8; Speed from 5
9	2012 May 14	C2.5	0.05[b]	0.40[a]	648	Event in 6; Speed from 9

Notes.
[a]0.32–0.45 MeV/nucleon.
[b]0.50–2.00 MeV/nucleon.
[c]0.45–0.64 MeV/nucleon.
References. (1) Bučík et al. (2016a), (2) Nitta et al. (2014), (3) Warmuth and Mann (2011), (4) Bučík et al. (2015), (5) Nitta et al. (2013), (6) Nitta et al. (2015), (7) Muhr et al. (2014), (8) Bučík et al. (2018), (9) Shen et al. (2018a).

4.4 CMEs

Not all ISEP events with EUV waves were found to be associated with CMEs. In some events only weak coronal outflows accompanied EUV waves. Generally, the associated CMEs were slow. Half of the ISEP events with EUV waves were accompanied by CMEs with a speed of ≲300 km/s and a width of ~50° (Bučík et al., 2016a). The ISEP events associated with EUV waves in the study of Nitta et al. (2015) had a speed of ~300 km/s and a width of ~50°. One ISEP event with a EUV wave in the study of Cohen et al. (2021) was accompanied by a CME with a speed of 450 km/s and a width of 18°. The other event was without a reported CME.

4.5 Jets

In several ISEP events, EUV waves occurred together with jets (Nitta et al., 2015; Bučík et al., 2015, 2016a); in other events only EUV waves were seen, possibly overwhelming the jet activity. An open question is the connection between jets and EUV waves in ISEP events and, ultimately, whether the energy spectra and the H abundance variations can be related to the jet-like CMEs or EUV waves.

Only a few papers have examined the jet's association with EUV waves. Zheng et al. (2012a,b) reported two EUV waves that were triggered by a jet. In one case the EUV wave was associated with a slow CME. Shen et al. (2018b) studied two EUV waves that were not associated with CME but were driven by loop expansion initiated by an accompanied jet. Shen et al. (2018a) analyzed four recurrent jets, where each jet was accompanied by a narrow EUV wave ahead of the jet. In their study, only the last EUV wave was associated with (jet-like) CME. Miao et al. (2018) examined a EUV wave, associated with a slow CME, that appeared on top of the jet. These papers do not address an association with energetic particles. However, they show the EUV waves speed much higher than the corresponding jet speed. The authors pointed out that based on the properties (amplitude, speed, negative acceleration), these EUV waves should be regarded as fast magnetosonic waves or shocks.

4.6 Longitude Spread

Several authors discussed that the EUV waves in GSEP events may be linked with the injection of particles when the wave front intersects spacecraft magnetic foot-point (e.g., Krucker et al., 1999; Torsti et al., 1999), leading to a wide-longitude particle spread in the heliosphere (e.g., Nitta, 2012; Rouillard et al., 2012; Park et al., 2013; Park et al., 2015; Lario et al., 2014; Richardson et al., 2014). Lario et al. (2014) suggested that particles can also be accelerated at high altitudes without leaving EUV trace at the solar disk.

Interestingly, all nine ISEP events measured on widely separated (~40°–80° in longitude) spacecraft (Wiedenbeck et al., 2013) were associated with EUV waves (Nitta et al., 2015; Bučík et al., 2016a). In some cases, the waves were seen to cross the spacecraft magnetic foot-point (Bučík et al., 2016a). It has been discussed that the EUV waves may be also connected with widespread ISEP events (Nitta et al., 2015; Zhang and Zhao, 2017). The question is if EUV waves in small ISEP events directly accelerate particles or if they act indirectly, e.g., trigger the particle release by the expanding fronts (Krucker et al., 1999).

Other mechanisms for the wide longitude spread of ^{3}He-rich SEPs, in particular, cross-field diffusion and distortion of magnetic field lines by a CME, have been discussed elsewhere (e.g., Wiedenbeck et al., 2013).

5 CONCLUSION

Previous works have suggested that the EUV waves in solar sources of ISEP events may be related to some features of these events, such as energy spectra variations, ion delays, and the wide longitude spread of energetic particles. The EUV wave speed was determined only in a few ISEP events with values ranging between ~260 and 650 km/s. The waves were observed together with jets or without jets, and they generally were accompanied by slow CMEs, or even CMEs were not observed. In some ISEP events, specifically in those without a CME, EUV waves were probably triggered by jets.

New space missions at a close distance from the Sun, Parker Solar Probe, and Solar Orbiter may bring new insights on the role of EUV waves in ISEP events (see Wiedenbeck et al., 2020; Cohen et al., 2021; Mason et al., 2021; Bučík et al., 2021, for the first reported ISEP events from these missions). For instance, measurements made close to the source of ISEP events remove uncertainties due to interplanetary transport effects.

AUTHOR CONTRIBUTIONS

The author confirms being the sole contributor of this work and has approved it for publication.

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