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SPECIALTY SECTION

This article was submitted to Space
Physics, a section of the journal
Frontiers in Astronomy and Space
Sciences

RECEIVED 20 January 2023

ACCEPTED 14 February 2023

PUBLISHED 14 March 2023

CITATION

Nitta NV, Bučik R, Mason GM, Ho GC,
Cohen CMS, Gómez-Herrero R, Wang L
and Balmaceda LA (2023), Solar activities
associated with ^3He -rich solar energetic
particle events observed by Solar Orbiter.
Front. Astron. Space Sci. 10:1148467.
doi: 10.3389/fspas.2023.1148467

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Solar activities associated with ^3He -rich solar energetic particle events observed by Solar Orbiter

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A series of ^3He -rich solar energetic particle (SEP) events was observed by Solar Orbiter in May 2021 at a radial distance of 0.95 AU. An isolated active region AR 12824 was likely the ultimate source of these SEP events. The period of the enhanced flux of ^3He was also a period of frequent type III bursts in the decametric–hectometric range, confirming their close relationship. As in past studies, we try to find the solar activities possibly responsible for ^3He -rich SEP events, using the type III bursts close to the particle injection times estimated from the velocity dispersion. But this exercise is not as straightforward as in many of the past studies since the region produced many more type III bursts and jet-like eruptions than the SEP injections. We may generalize the solar activities for the ^3He -rich SEP events in question as coronal jets, but their appearances do not necessarily conform to classic jets that consist of a footpoint and a spire. Conversely, such jets often did not accompany type III bursts. The areas that produced jet-like eruptions changed within the active region from the first to the second set of ^3He -rich SEP events, which may be related to the extended coronal mass ejection that launched stealthily.

KEYWORDS

Sun, solar energetic particles, radio emission, UV radiation, solar jets, elemental abundances

1 Introduction

A defining attribute of the so-called impulsive solar energetic particle (SEP) events is anomalies in ionic composition, especially the enhancement of the $^3\text{He}/^4\text{He}$ ratio by up to 10^4 of the typical values in the corona and solar wind. Since their discovery many decades ago (e.g., Schaeffer and Zähringer, 1962; Hsieh and Simpson, 1970), “ ^3He -rich flares” puzzled many workers because most of them showed either no or very weak flare emissions (Kahler et al., 1987; Reames et al., 1988), even though they were associated with type III radio bursts below 2 MHz (Reames and Stone, 1986) and *in situ* electron events observed

in the 10–100 keV range (Reames et al., 1985)¹. To avoid possible confusion that the word “impulsive” may incur, we call this type of events “³He-rich” SEP events throughout the paper. A new insight was obtained by Kahler et al. (2001), who found the association of ³He-rich SEP events with narrow coronal mass ejections (CMEs) observed by the Large Angle Spectroscopic Coronagraph (Brueckner et al., 1995) on board the Solar and Heliospheric Observatory (SOHO). Some of these CMEs started off as coronal jets observed by the Extreme-Ultraviolet Imaging Telescope (Delaboudinière et al., 1995) also on board SOHO, as was found by Wang et al. (2006), who showed for the first time that ³He-rich SEP events were temporally correlated with recurrent jets in coronal hole boundaries.

Since the Wang et al. (2006) paper, it has been proclaimed that coronal jets are responsible for ³He-rich SEP events, even though the original paper primarily discussed the importance of the interaction between the base of an open field line and a nearby bipole. Jets have been emphasized in some of the review articles on ³He-rich SEP events (e.g., Mason, 2007; Bučík, 2020; Reames, 2021). It is not difficult to find clear examples of jets in EUV or soft X-rays temporally correlated with ³He-rich SEP events (Nitta et al., 2006, 2008; 2015; Wang et al., 2006; Bučík et al., 2014, 2018). However, these individual cases may not ensure that jets are a necessary condition for ³He-rich SEP events. Indeed, in ensemble studies, the association rate of ³He-rich SEP events with jets is not necessarily high, only up to ~50% (Nitta et al., 2006, 2015; Bučík et al., 2021). We may attribute the failure to capture jets by EIT to its limitation in spatial resolution, sensitivity, cadence and temperature coverage. However, we may not necessarily observe jets around the estimated injection times of ³He particles even in data from the Atmospheric Imaging Assembly (Lemen et al., 2012) on board the Solar Dynamics Observatory (SDO). The other forms of solar activities associated with ³He-rich SEP events may include compact brightenings, eruptions more extended than a jet, EUV waves, etc. (e.g., Nitta et al., 2015; Bučík et al., 2016, 2021; Bučík, 2022).

In this paper we study ³He-rich SEP events observed by Solar Orbiter in May 2021 (Ho et al., 2022) to further our understanding of the solar sources of this type of SEP event. Ho et al. (2022) focused on the “dropout” phenomenon (Giacalone et al., 2000; Mazur et al., 2000; Chollet and Giacalone, 2008) that was observed during the period in which six clear ion injections were identified. Our emphasis is on solar activities observed by AIA during the same period. Unlike many previous examples of isolated ³He-rich SEP events, we note multiple type III bursts and jet-like activities around the estimated times of ion injections, and their associations with ³He-rich SEP events may be more complicated. After giving an overview of the series of ³He-rich SEP events in Section 2, we describe in Section 3 solar activities that may be related to ³He-rich SEP events, using snapshots from movies that reveal them in detail. Some of the movies are included in Supplementary Material. In Section 4 we summarize what we learn from this study concerning the origin of ³He-rich SEP events in terms of jets. While we mention

solar activities or transients, we specifically look for those that have appearances and properties in common with coronal jets. Coronal jets are ubiquitous phenomena and are actively investigated (see recent reviews by Raouafi et al., 2016; Shen, 2021), irrespective of their possible roles in the production of ³He-rich SEP events. We note, however, that there is no universal definition of coronal jets, quantitatively speaking, and that identifying them is somewhat subjective.

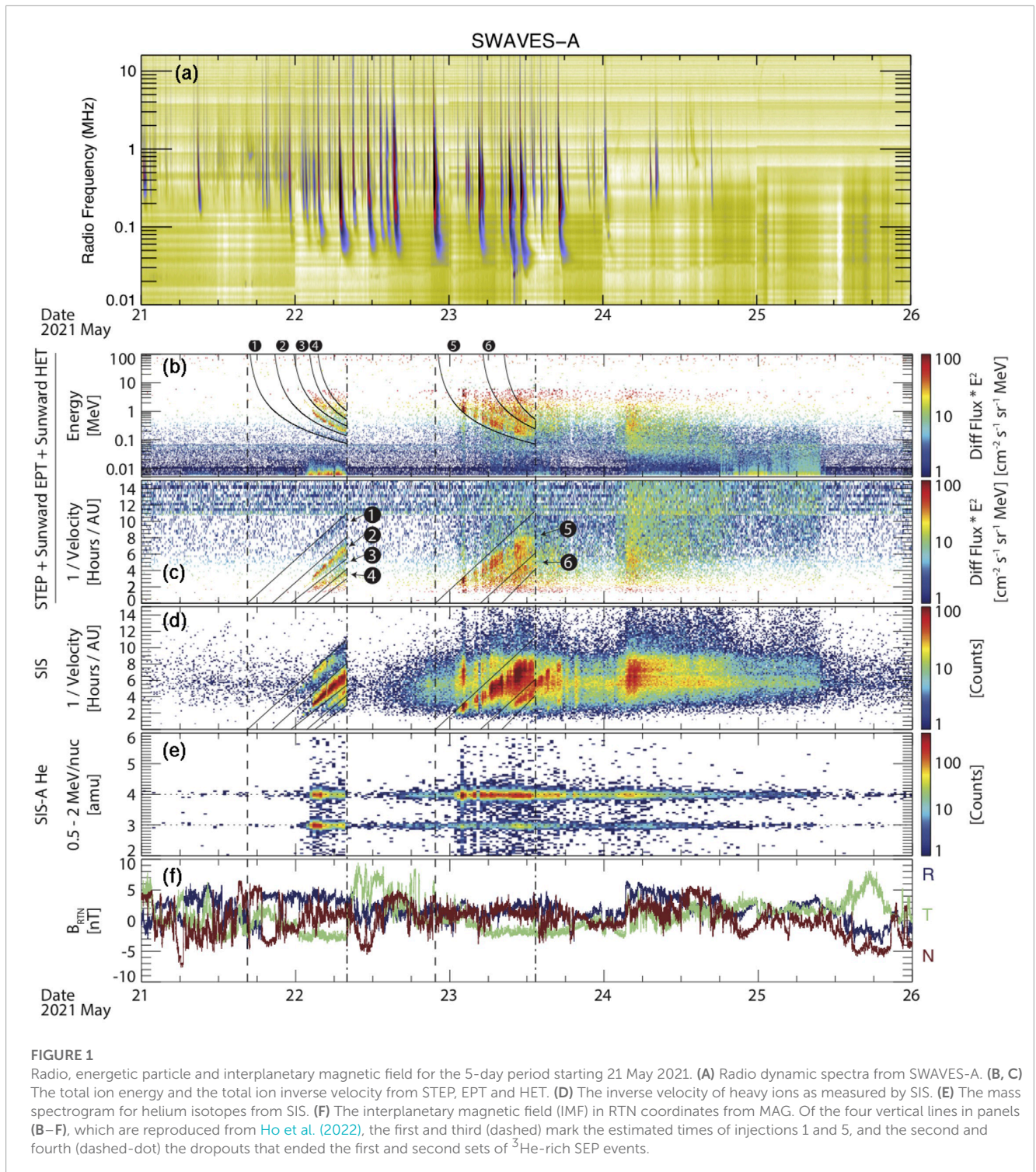
2 Overview of the 21–24 May 2021 period

In late May 2021, Solar Orbiter observed a series of ³He-rich SEP events (Ho et al., 2022). Figure 1 combines a decametric-hectometric (DH) radio dynamic spectrum (Figure 1A) from the Radio and Plasma Wave Investigation on the STEREO Mission (Bougeret et al., 2008) on board STEREO-A (hereafter SWAVES-A) with Solar Orbiter data [Figures 1B–F, reproduced from Ho et al. (2022)]. Figures 1B–E show SEP data from the Energetic Particle Detector (Rodríguez-Pacheco et al., 2020) and (Figure 1F) the interplanetary magnetic field (IMF) in RTN coordinates from the Solar Orbiter magnetometer (Horbury et al., 2020).

Concerning SEP data, Figures 1B–C show, respectively, the total energy and inverse velocity of ions (mostly protons) in the 10 keV–100 MeV range, as measured by the three Sunward-facing sensors of EPD, i.e., the SupraThermal Electrons and Protons (STEP), the Electron Proton Telescope (EPT), and the High-Energy Telescope (HET). The ion composition measurements Figures 1D–E come from the Suprathermal Ion Spectrograph (SIS), another component of EPD, showing the inverse velocity of heavy ions (Figure 1D) and the mass spectrogram for helium isotopes (Figure 1E). Ho et al. (2022) identified six ion events during 21–23 May, with the first four grouped into the first set, followed by the last two in the second set after a long dropout. They are numbered Figures 1B–C. They are all ³He-rich impulsive SEP events, according to the helium ion masses Figure 1E. They occurred in a period of enhanced type III radio activity, confirming their close relationship.

On 22 May 2021, Solar Orbiter was located at ~0.95 AU from the Sun and ~98° east of the Sun–Earth line as in Figure 2. Assuming the nominal Parker spiral field lines, it was expected to be connected to the eastern hemisphere of the Sun in Earth view. According to the Solar Orbiter magnetic field connection tool (Rouillard et al., 2020), Solar Orbiter was connected to AR 12824, which was the only sunspot region visible from Earth. It is indicated by the cyan box in Figure 3A, which shows an AIA full-disk image in the 211 Å channel. The heliographic coordinates of the region are given in the NOAA region list as N20E27 at 00:00 UT on 22 May 2021. Other bright areas seen in Figure 3A never evolved to be numbered active regions except for the one on the east limb, which became AR 12825, a short-lived region that stayed numbered only during 24–25 May. In Figure 3B, we show a line-of-sight magnetogram of the region indicated by the cyan box Figure 3A. It is from the Helioseismic and Magnetic Imager (Scherrer et al., 2012) on board SDO. Green dots indicate the footpoints of open field lines as calculated with the SolarSoft package of the potential field source surface (PFSS) model (Schrijver and De Rosa, 2003). They are distributed in the southern

¹ Note that, although near-relativistic electron events are statistically correlated with the periods of ³He enhancement (Wang et al., 2012), individual electron events may not be (e.g., Ageda et al., 2014)

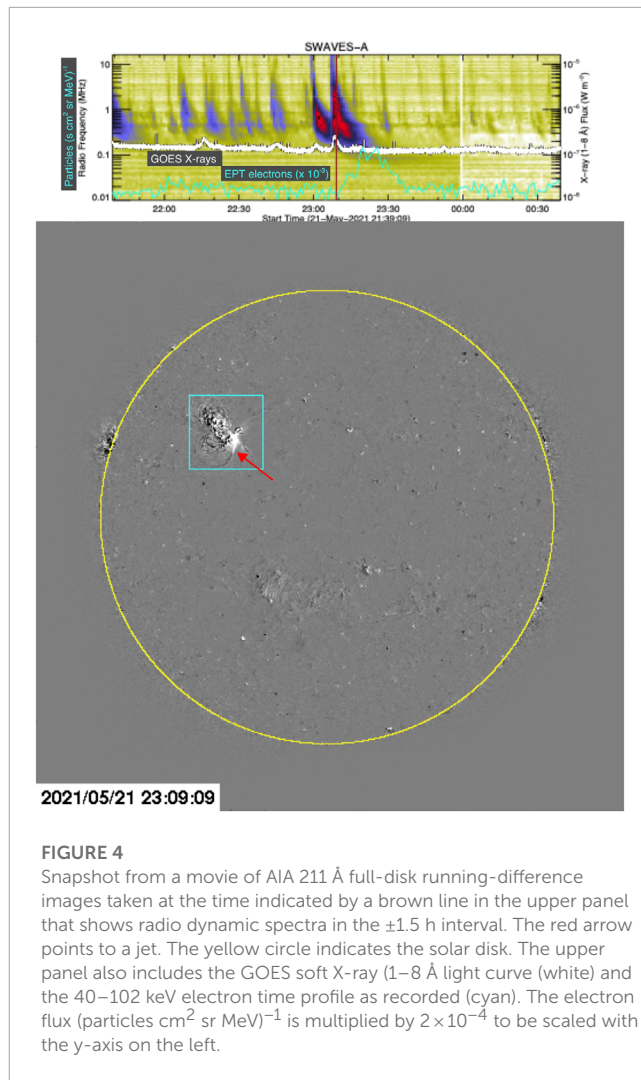
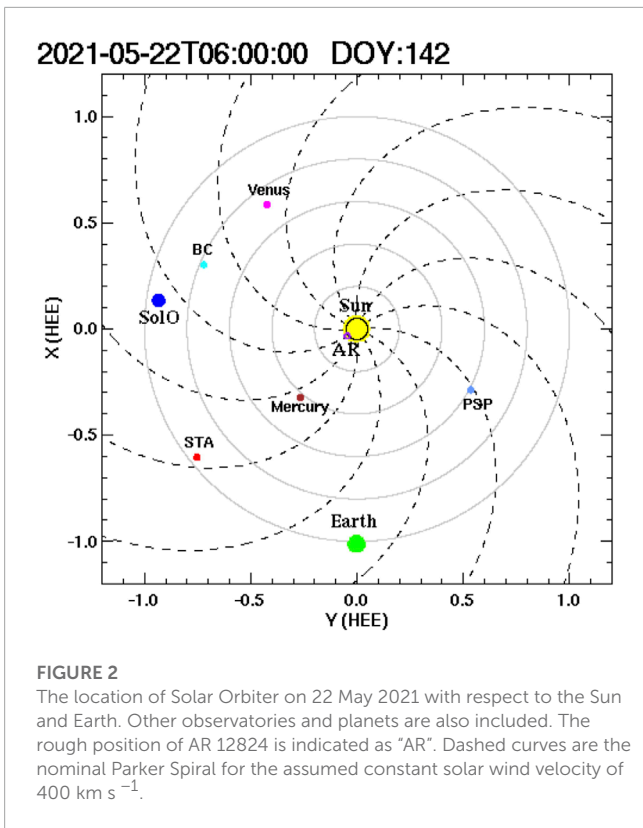


to northwestern perimeter of the leading spot of AR 12824, where we observe much of transient activities as shown in [Section 3](#).

3 Observations

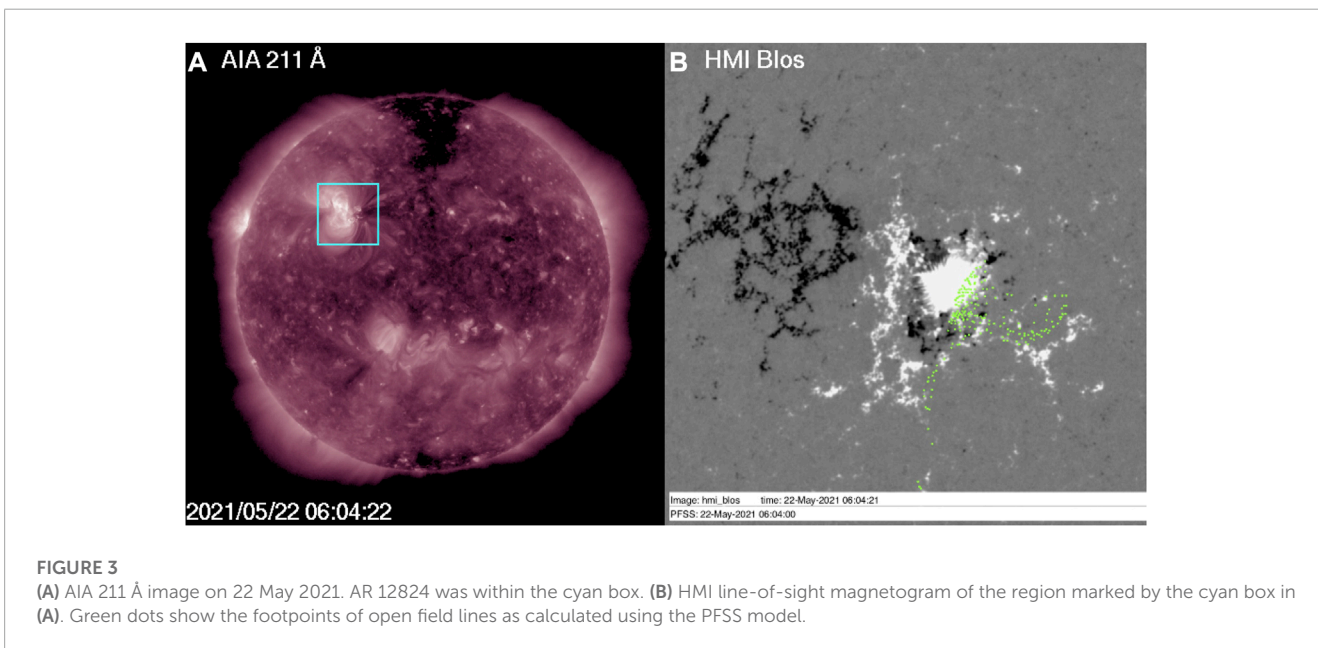
In order to identify the solar activities that likely contributed to the production of ^3He particles during 21–23 May 2021, we follow

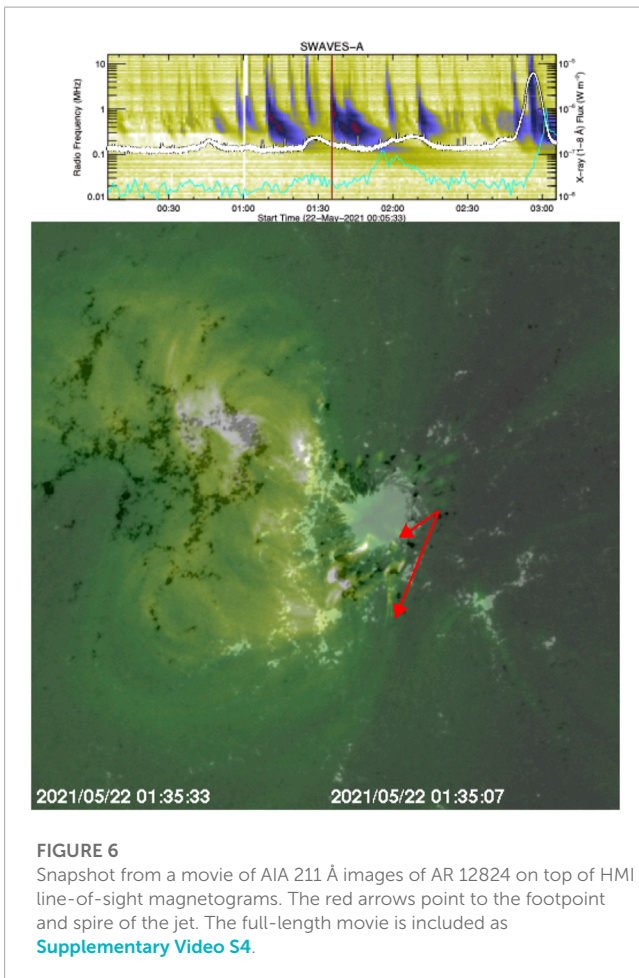
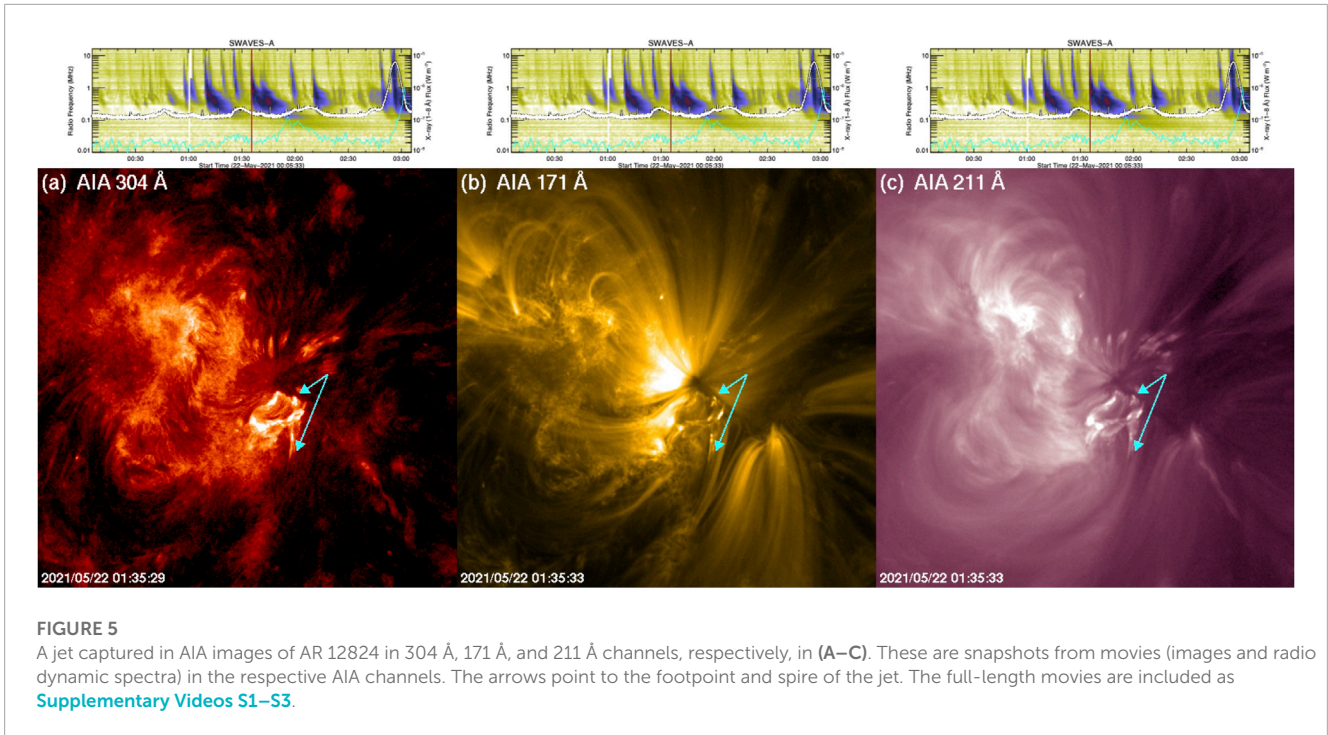
the procedure used in previous studies ([Nitta et al., 2006, 2015](#)). That is, to find a type III burst in radio dynamic spectra around the estimated time of particle injection and then to search for transient phenomena in EUV images within a few minutes after the start of the type III burst. We base this exercise on the six particle injection times listed in [Ho et al. \(2022\)](#). In addition, since AR 12824 exhibits so many type III bursts and jets, we also address a broader question outside the SEP context about which type IIIs are associated with a



jet, and which jets are associated with a type III burst. This may in turn help clarify whether jets are a necessary condition for ^3He -rich SEP events.

Most of the findings in this paper come from closely comparing AIA images with radio dynamic spectra from SWAVES-A. We use SWAVES-A 1-min data because they allow us to easily plot DH





radio dynamic spectra, on which type III radio bursts are identified by visual inspection. Similar data from WAVES on Wind had a ~17 h long data gap on 22 May 2021 while the $^3\text{He}/^4\text{He}$ ratio was elevated ([Figure 1E](#)). We produced movies of AIA images in 24 s cadence (just excluding those with the automatic exposure control on) over a 3-day period starting at 09 UT on 21 May 2021. This period covers the six particle injections ([Ho et al., 2022](#)) with a 0.5–1 day margin before and after. A snapshot from one of the movies is shown in [Figure 4](#). Above the AIA image taken at time t , a SWAVES-A dynamic spectrum is shown over the interval of $[t-1.5 \text{ h}, t+1.5 \text{ h}]$. Viewing frames in this layout as a movie, we can study, in reasonable detail, the association of type III bursts and transient activities including jets over a long period (e.g., 3 days). The upper panel also shows the GOES 1–8 Å light curve (white) and the time profile of 40–102 keV electrons from EPT (cyan) that inform us about how the type III bursts involve solar flares and electron events, respectively. [Figure 4](#) is a snapshot from the movie of 211 Å full-disk running difference images. The red arrow point to a small jet barely noticeable. The purpose of this movie is to find whether a given type III burst is correlated with a transient activity within AR 12824. It turns out that almost all the type III bursts during our 3-day period were from AR 12824.

To isolate transient activities more clearly, we zoom in on the active region, bounded by the cyan box in [Figures 3A, 4](#). Moreover, we examine AIA images in multiple channels to avoid missing jets in case they may appear in a narrow temperature range. As in the snapshot shown in [Figure 5](#), however, most jets are observed in all of the AIA 304 Å (0.089 MK), 171 Å (0.79 MK), and 211 Å (1.78 MK) channels, and their appearances are similar across these channels. The full-length movies of these images are included as [Supplementary Videos S1–S3](#). They show that many typical jets

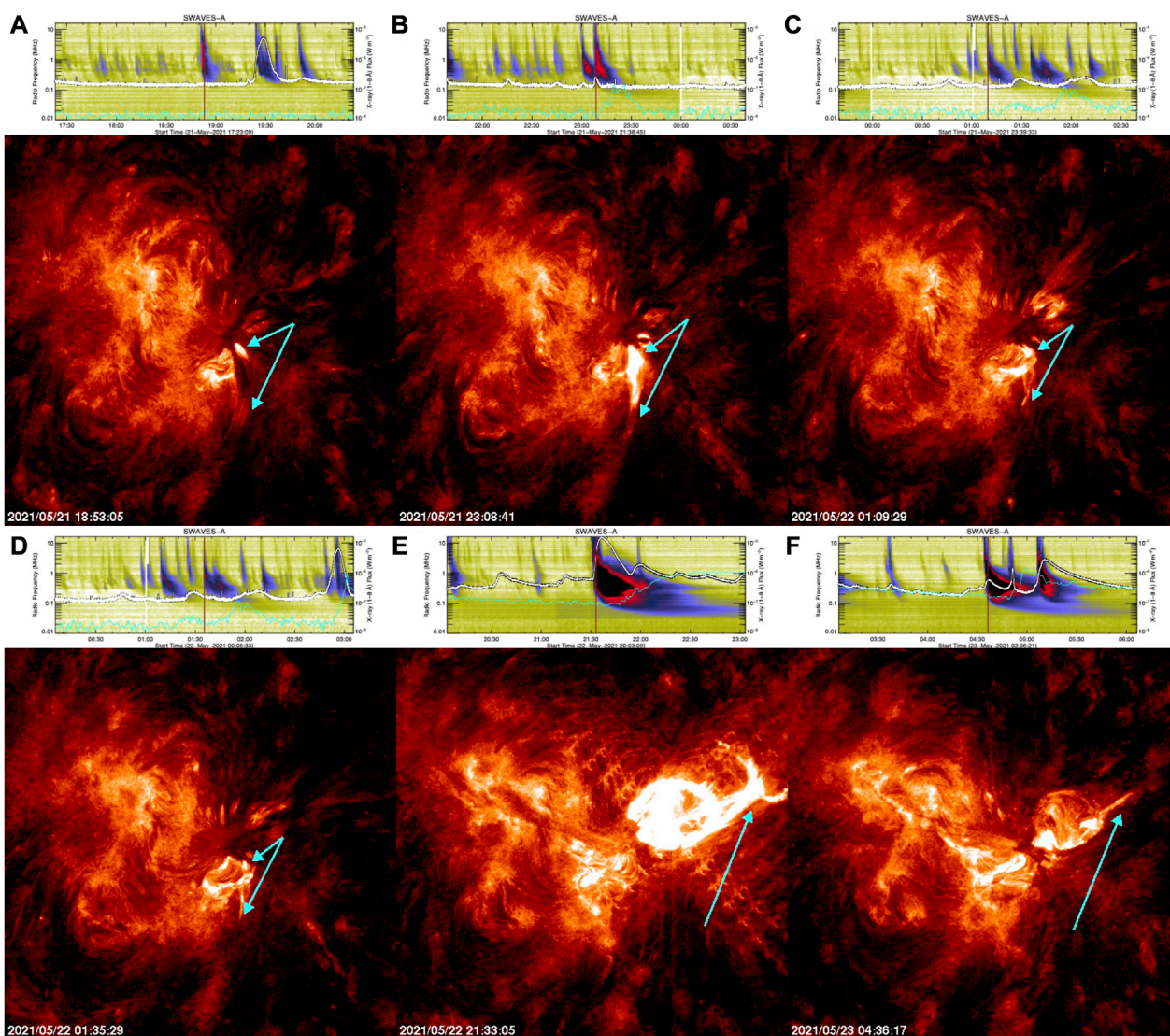
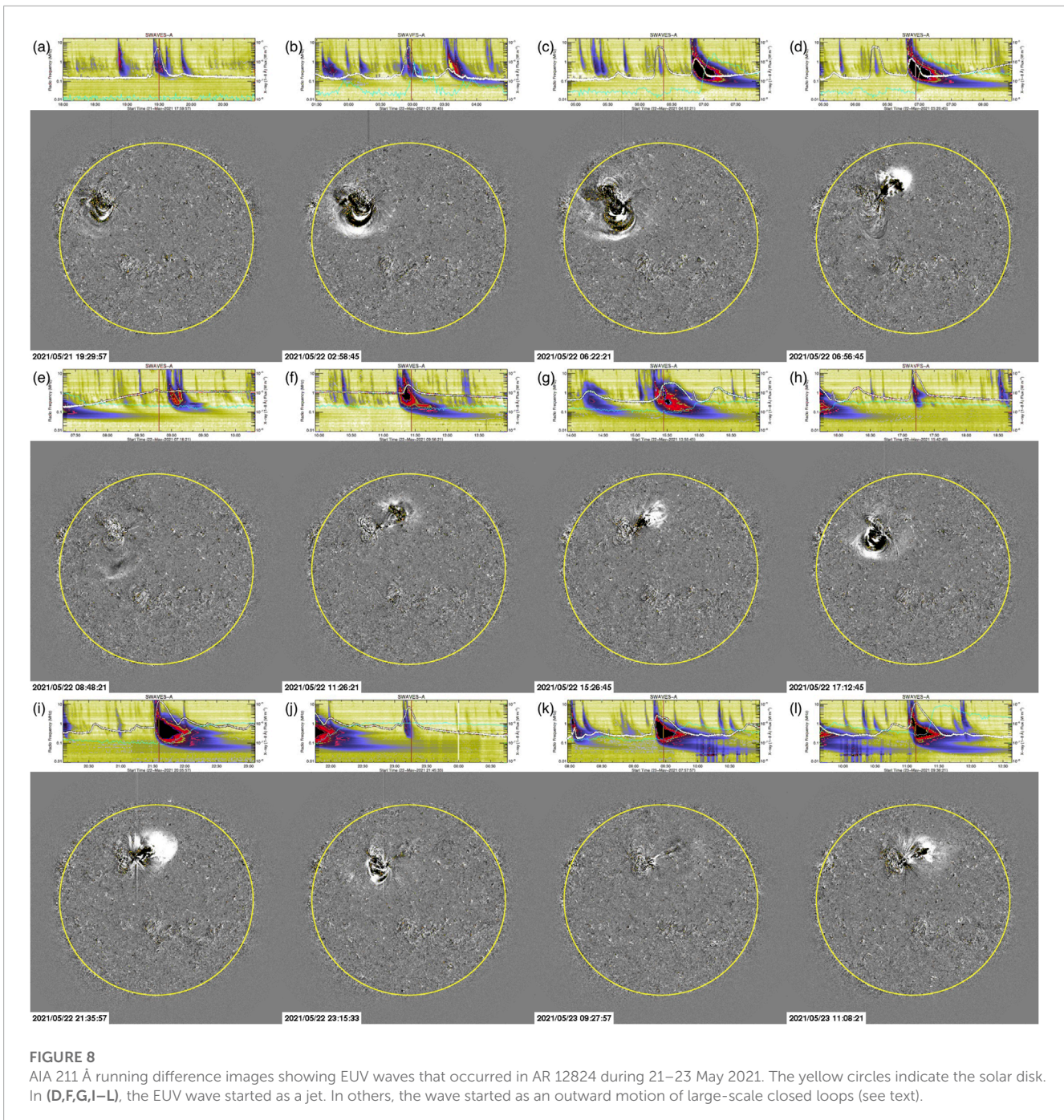


FIGURE 7
 Jet-like eruptions around the times of type III bursts. In (A–D), two arrows point to the footpoint and spire. In (E,F), the arrow points to the spire or the upper part of the ejections. These eruptions likely contributed to the six ³He-rich SEP events.

consisting of a footpoint brightening and a spire that delineates a collimated outflow (e.g., Muly et al., 2016; Panesar et al., 2016) are ejected toward south and west. Ejections toward northwest are often more extended than a classic jet and may be classified as surges. In order to inform the magnetic origins of these transients, Figure 6, a snapshot from Supplementary Video S4, shows an AIA 211 Å image over a line-of-sight magnetogram from HMI. The jet-like activities such as the one indicated by the red arrows in Figure 6, are related to small magnetic elements around the leading sunspot of AR 12824, which look like moving magnetic features (MMFs) (see Harvey and Harvey, 1973; Shine and Title, 2000; Innes et al., 2016).

Now we discuss the candidates of solar activity that may be related to the series of ³He-rich SEP events during 21–23 May 2021. See Table 1 in Ho et al. (2022) for their estimated injection times and other important properties such as ³He/⁴He ratios. We hereafter refer to these individual SEP events as Event 1–Event 6,

whose candidate sources are illustrated in Figures 7A–F. For Event 1, we cannot readily find a candidate that accounts for the estimated injection time of 21 May 16:05. However, the first major type III burst at 18:52 should be the best option despite the long delay. It appears that the velocity dispersion for this injection may not be approximated by a straight line, and that the estimated injection time could be off by a few hours. This type III burst was correlated with a jet-like eruption toward south with a marginal spire (Figure 7A). For event 2, the estimated injection time is 21 May 22:00. Two successive jets and type III bursts at 21 May 22:59 and 23:08 seem to be a good candidate. As seen in Figure 7B, their locations are close to that of the earlier (18:52) event. Moreover, the 23:08 event is accompanied by an electron event. The estimated injection times for Event 3 and Event 4 are 22 May 00:40 and 02:00, respectively. We find two type III bursts that are not too much apart from these times and are accompanied by electron events. They occur at 22



May 01:09 and 01:35 (Figures 7C, D). They again correspond to jets emanating from the southwestern periphery of the leading sunspot of AR 12824 and directed south. Another type III burst at 22 May 02:55 (also a C6.1 flare) may be in the time range to be considered for Event 4, especially since it is accompanied by an electron event. But it is linked to a global EUV wave, which is usually not associated with ^3He -rich SEP events (but see, for example, Nitta et al., 2015; Bučík et al., 2015, 2016; Bučík, 2022). Events 5 and 6 occur after a long dropout. Their estimated injection times are 22 May 20:50 and 23 May 04:20. The most promising type III bursts, especially because of the accompanying electron events, are the ones at 22 May 21:32 and 23 May 04:36, respectively (Figures 7E, F). They occur at the

northwestern to western perimeter of the leading sunspot. Note that Event 5 appears to be more spatially extended and it may be classified as a surge. It is also an M1.4 flare. Incidentally, the baseline of the electron time profile shifted upward by an order of magnitude after the type III burst and C1.3 flare on 22 May around 06:50 UT. Further discussion of this phenomenon is beyond the scope of this work and will be explored in future papers.

AR 12824 produced a number of EUV waves, starting on 17 May 2021 as documented in https://aia.lmsal.com/AIA_Waves. Several events were observed on 17 and 18 May, but not on 19–20 May. They almost always followed the pattern of starting as a jet-like narrow ejection, followed by a large wave-like feature once the jet material

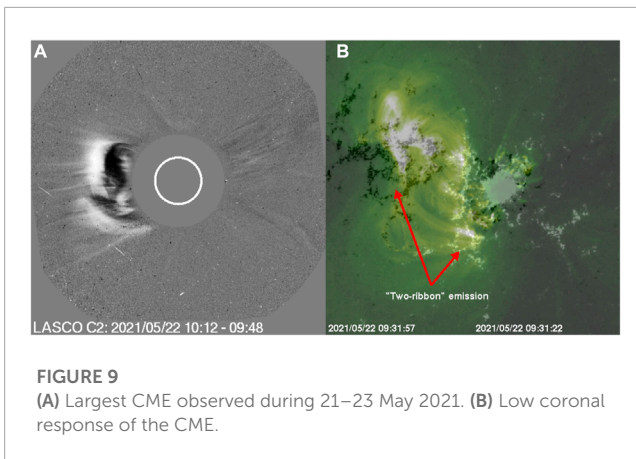


FIGURE 9
(A) Largest CME observed during 21–23 May 2021. (B) Low coronal response of the CME.

hit a remote quiescent region that was apparently magnetically connected. During the 3-day period starting 21 May 2021 09:00, there were at least 12 EUV waves from AR 12824 as shown in Figure 8. There were two types. One type started as a jet or a surge and gave rise to an EUV wave only at large distances, similar to those observed during 17–18 May. Several of the fast jets or surges belong to this type (Figures 8D,E,G,I–L). They are always associated with strong type III bursts and could also be with ^3He -rich SEP events. The event Figure 8I is the same event shown in Figure 7E. Another type started as an outward motion of large-scale closed loops. These events may or may not be associated with a type III burst and probably not related to ^3He -rich SEP events. Note that none of these EUV waves are associated with a clear CME observed by LASCO. This may be partly because of the location of AR 12824, which may prevent a narrow CME from being observed. Interestingly, the most prominent CME from this region (Figure 9) occurred without obvious low-coronal signatures like a stealth CME (Robbrecht et al., 2009; D’Huys et al., 2014; Nitta and Mulligan, 2017) on 22 May, shortly before the diffuse EUV wave shown in Figure 8E. There was no clear eruption, but the GOES X-ray flux slowly built up. In Figure 9B we note emission like a two-ribbon flare on the eastern side of the leading sunspot and the plage region in the following polarity. This CME may be related to the dropout even though its direct cause appears to be variations of IMF (~ 08 UT on 22 May, see Figure 1F). It may have altered the magnetic field connection to Solar Orbiter.

4 Discussion

A series of ^3He -rich SEP events occurred in late May 2021 and were observed by Solar Orbiter (Ho et al., 2022). They provide us an opportunity to reevaluate the widely proclaimed link between ^3He -rich SEP events and coronal jets (Wang et al., 2006; Mason, 2007; Bučík, 2020; Reames, 2021). In this period there was only one active region (AR 12824) that could have been connected to Solar Orbiter, which in principle makes the correlative study easier because solar transients from this region would have ultimately been responsible for the production of ^3He . The six ^3He -rich SEP events generally show clear velocity dispersions, suggestive of their separate injections in the solar corona. This is somewhat less clear

in Event 1. As in previous studies, type III bursts are used to limit the time range in which we look for solar transients in AIA images. This may be justified because the period of elevated $^3\text{He}/^4\text{He}$ ratio coincides with frequent type III bursts, except for the long “dropout” period (roughly 08–22 UT on 22 May, see Figure 1). The challenge pertaining to this particular period is to single out the solar transient for each of the ^3He -rich SEP events because multiple jet-like eruptions are seen within one or 2 minutes from the type III burst, coming from different areas around the sunspot, in the range of 180° (south)– 30° (northwest) from solar north. Even if we find the candidate events as in Figure 7, we cannot rule out the possibility that other jets close to the SEP injection time, irrespective of their type III association, may have contributed to the observed ^3He . The videos of images in 24 s cadence, included in Supplementary Material, capture many instances of jet-like eruptions within a minute or two, which would have been not possible in images taken with poorer temporal resolution.

The solar transients temporally correlated with type III bursts show various appearances, as found in Supplementary Videos S1–S3, whose snapshots are shown in Figure 5. Specifically, it is hard to isolate jets from other forms of activity including compact brightenings, wider eruptions, and EUV waves. Out of the 118 type III bursts during the 3-day period starting at 21 May 2021 09:00 UT (which include the six that are associated with ^3He -rich SEP events), only 63 ($\sim 53\%$) may be classified as classic jets. But brightenings ($\sim 19\%$) may be generalized to be jets, as some unspecified observational conditions may make it hard to find the spire. Whether to identify wider eruptions ($\sim 28\%$) with jets may be a matter of subjective decision. Despite extensive studies of jets (see recent reviews by Raouafi et al., 2016; Shen, 2021), there seems to be no universal definition of jets that can be used for their automated detection. Indeed, SDO initially had a plan to automatically detect and characterize jets (Martens et al., 2012), but it has not been implemented in the AIA data pipeline. Jets (and many other phenomena) included in the Heliophysics Event Knowledgebase (Hurlburt et al., 2012)² have been detected manually by scientists *via* visual inspection.

Conversely, many classic jets that consist of a footpoint and spire do not appear correlated with a type III burst. This may simply reflect the limited sensitivity of the radio instruments, but SWAVES-A data show many marginal type III bursts, including those that appear repeatedly in limited time intervals and in limited frequency ranges. A more likely reason may be the lack of non-thermal electron beams escaping along open field lines. Following the detection of hard X-ray emission from the base of a jet by Yokkoh (Nitta, 1997), RHESSI observed many examples of jets with hard X-ray emission even from the corona, some of which was determined to be of non-thermal origin (Bain and Fletcher, 2009; Krucker et al., 2011; Glesener et al., 2012; Musset et al., 2020). But these may be a small subset of jets. We also point out that type III bursts are characteristically missing from jets that come from polar coronal holes, such as those studied by Sterling et al. (2015, 2022).

² <https://www.lmsal.com/hek/>

It is important to know which jet-like solar transients are more likely associated with ^3He -rich SEP events and how they may affect the properties of the latter. Unfortunately, it is hard to distinguish the jets associated with ^3He -rich SEP events in terms of their basic properties including size, speed, etc. In our examples, Events 1–4 are associated with small jets from the southern perimeter of the leading spot, whereas Events 5–6 with eruptions larger than typical jets that are ejected from an area northwest of the spot. The projected lengths of the jets excluding the footpoints are <35 Mm, and >50 Mm, respectively, for the first and second sets. According to Ho et al. (2022), with an exception of Event 1, the first four events have higher $^3\text{He}/^4\text{He}$ ratio at 385 keV/n (0.6–1.4) than the last two (≤ 0.1). To expand our inquiry of which jets are associated with ^3He -rich SEP events, it may be a worthwhile effort to find how they are related to other phenomena including coronal bright points (Madjarska, 2019) and plumes (Poletto, 2015). Lastly, we may ask how important or relevant is the presence of a flux rope in jet-like eruptions as in the scenario of mini-filament eruptions (Sterling et al., 2015; Wyper et al., 2017) in the context of escape of particles (Masson et al., 2013) including ^3He .

Data availability statement

SDO data are available at JSOC (<http://jsoc.stanford.edu/>). STEREO/WAVES data are downloaded from the STEREO Science Center (<https://stereo-ssc.nascom.nasa.gov/>). The Solar Orbiter data are available at <https://soar.esac.esa.int/soar/>.

Author contributions

NN processed AIA and SWAVES-A data. RB and LW encouraged the lead author to write a paper for the topical volume. GM first notified the lead author of the SEP events in question, and further updated SEP analysis. GH provided SEP information including his paper on the same events before official publication. CC helped with interpretation of SEP data. RG-H provided electron data. LB discussed with the lead author about the effect of image cadence on the appearance of transient phenomena.

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Funding

The work of NN was supported by NASA grants 80NSSC18K1126 and 80NSSC20K0287. RB acknowledges support from a NASA grant 80NSSC22K0757. CC was supported by NASA grants 80NSSC18K0223 and 80NSSC21K1512. RG-H acknowledges the financial support of the Spanish MINCIN Project PID2019-104863RBI00/AEI/10.13039/501100011033.

Acknowledgments

We acknowledge the International Space Science Institute (ISSI) for their support of International Team “Origins of ^3He -Rich Solar Energetic Particles” (<https://www.issibern.ch/teams/origin3henrgpart/>).

Conflict of interest

Author NN was employed by Lockheed Martin Advanced Technology Center.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fspas.2023.1148467/full#supplementary-material>

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