

^3He -rich solar energetic particles: Solar sources

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Abstract ^3He -rich solar energetic particles (SEPs), showing up to a 10,000-fold abundance enhancement of rare elements like ^3He or ultra-heavy nuclei, have been a puzzle for more than 50 years. One reason for the current lack of understanding of ^3He -rich SEPs is the difficulty resolving the source regions of these commonly occurring events. Since their discovery, there has been strong evidence that ^3He -rich SEP production is associated with flares on the Sun. Anomalous abundances of ^3He -rich SEPs have been attributed to a unique acceleration mechanism that must routinely operate at flare sites. Flares associated with ^3He -rich SEPs have been often observed in jet-like forms indicating an acceleration in magnetic reconnection involving field lines open to interplanetary space. Owing to a fleet of spacecraft around the Sun, providing a greatly improved resolution of solar imaging observations, ^3He -rich SEP sources are now explored in unprecedented detail. This paper outlines the current understanding of ^3He -rich SEPs, mainly focusing on their solar sources.

Keywords Acceleration of particles · Sun: flares · Sun: magnetic fields · Sun: particle emission

1 Introduction

^3He -rich solar energetic particles (SEPs) were discovered in the early 1960s (Schaeffer and Zähringer 1962) and since then they have been the focus of many experimental (e.g., Hsieh and Simpson 1970) and theoretical investigations (e.g., Fisk 1978). As their name indicates, ^3He -rich SEPs are characterized by the enormous

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enrichment of the rare isotope ^3He by factors of up to 10^4 above the solar wind or coronal abundance ($^3\text{He}/^4\text{He} \sim 4 \times 10^{-4}$ in the solar wind; Gloeckler and Geiss 1998). Heavy ($^{22}\text{Ne} - ^{56}\text{Fe}$) and ultra-heavy ions (mass >70 amu) are enhanced by a factor of 3–10 and >100 , respectively, independently of the amount of ^3He enhancement (Mason et al. 1986; Reames et al. 1994). It has been interpreted as evidence that different mechanisms are involved in the acceleration of the ^3He and the heavy ions. The abundance enhancement factor increases with atomic number (or mass) for heavier ions approximately as a power-law (Mason et al. 2004; Reames and Ng 2004). Furthermore, whereas with He the lighter isotope is enhanced, with heavier ions (e.g., Ne, Mg) heavier isotopes are enhanced (see Kocharov and Kocharov 1984; Mason 2007, for a review). ^3He -rich SEP events are a ubiquitous phenomenon with the rate of occurrence corresponding to $\sim 10^3$ events/yr (~ 1 MeV nucleon $^{-1}$ $^3\text{He}/^4\text{He} > 0.1$) on the visible solar disk at solar maximum (Reames et al. 1994; Wang et al. 2012).

Systematic research of ^3He -rich SEP sources started more than a decade ago using the *Solar Heliospheric Observatory* (SOHO) extreme ultraviolet (EUV) imaging observations (Wang et al. 2006; Nitta et al. 2006; Pick et al. 2006). Recent reviews on ^3He -rich SEP events (Mason 2007; Reames 2017) focus more on energetic ion characteristics obtained from in-situ measurements. In this paper we present new insights on ^3He -rich SEP sources provided by recent space missions such as the *Solar TERrestrial RELations Observatory* with two progressively separating spacecraft STEREO-A, -B, and the *Solar Dynamics Observatory* (SDO) with unprecedentedly high-resolution observations.

2 Soft X-rays flares

^3He -rich SEP events have been associated with minor (low intensity) soft X-ray (1–8 Å) GOES (mostly B- and C-class) flares (e.g., Nitta et al. 2006, 2015; Mason et al. 2009; Bučík et al. 2016a). Also an inverse correlation between the soft X-ray peak intensity and ^3He (ultra-heavy) enrichment has been reported (Reames et al. 1988; Reames and Ng 2004). This has been explained by arguing that in small flares the limited available energy is almost all absorbed by the rare ^3He and the heavy ions, while in large flares there is enough energy to accelerate more abundant elements which decreases the relative enrichment of the rare species (Reames and Ng 2004). ^3He -rich events have been termed impulsive SEP events based on the time-intensity profile of the associated X-ray flares. The ^3He -rich SEPs and X-rays may originate in different regions in the corona because ions are accelerated at reconnection sites on open field lines while flares involve reconnection on neighboring closed loops (Reames et al. 2014a). Often ^3He -rich SEP events are found without an observed X-ray flare (Kahler et al. 1987), showing a signal only in EUV (~ 100 – 200 Å) wavelengths (e.g., Nitta et al. 2006).

3 Cone of ions emission

Flares associated with ^3He -rich SEP events observed at the Earth were found to come from a limited region ($\sigma \sim 16^\circ$) on the western hemisphere ($\sim \text{W}57$) of the Sun

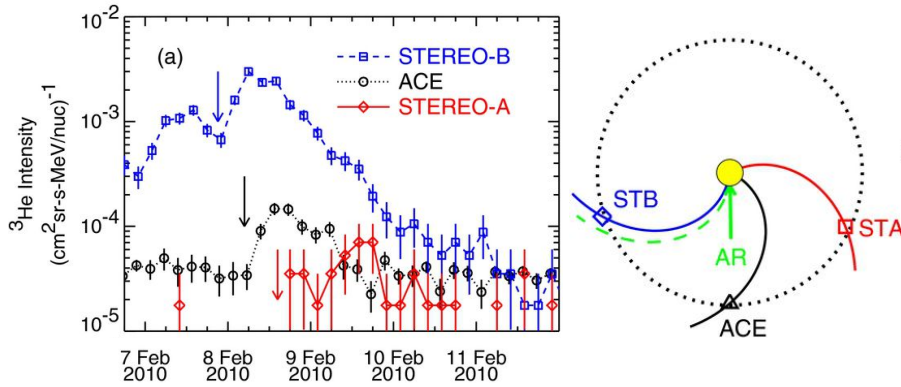


Fig. 1: (Left) The 2010 February 7 ^3He -rich SEP event measured on angularly separated spacecraft STEREO-A, -B ($\sim 3 \text{ MeV nucleon}^{-1}$) and ACE ($\sim 9 \text{ MeV nucleon}^{-1}$). (Right) The location of spacecraft and the source active region. Adapted from Wiedenbeck et al. (2013).

which is magnetically well-connected to the observer (e.g., Reames 1999). Imaging observations on the spacecraft (STEREO-A) angularly separated from Earth (ACE) have shown a significantly broader longitudinal distribution of source flares ($\sigma \sim 42^\circ$; Bučík et al. 2016a), inconsistent with simple interplanetary magnetic field spiral approximation even when combining with divergent coronal field lines from potential-field source-surface model (Nitta et al. 2015). The sensitivity of ion telescopes can affect the longitudinal distribution - the weak ion signal measured by ACE would have been below the threshold of past instruments. A wide cone of emission can be expected from measurements of ^3He -rich SEP events on angularly separated spacecraft (Wiedenbeck et al. 2013). Figure 1 shows the 2010 February 7 ^3He -rich SEP event measured at three widely ($>60^\circ$) separated spacecraft STEREO-A, -B, and ACE.

Several mechanisms have been discussed that contribute to the measured broad spatial distribution of ^3He -rich SEPs including large-scale coronal waves (c.f. Section 5), field lines meandering due to supergranular motions in the photosphere (e.g., Giacalone and Jokipii 2012; Zhang and Zhao 2017) where a small percentage of the field lines can make quite large excursions (e.g., Jokipii and Parker 1969), or separatrix S-web (Scott et al. 2018) where field lines from a narrow corridor, connecting low-latitude coronal holes with polar coronal holes, map to the extended longitudes in the heliosphere (e.g., Higginson et al. 2017).

4 Jets

Early studies of ^3He -rich SEP events showed an association with small area $\text{H}\alpha$ (6563 \AA) 'visible' flares (Zwickl et al. 1978; Reames et al. 1985; Kahler et al. 1987). Further studies have shown that flares associated with ^3He -rich SEPs are commonly observed as collimated or jet-like forms in EUV/X-ray images (Nitta et al. 2006, 2008, 2015; Bučík et al. 2014, 2018b; Chen et al. 2015; Wiedenbeck

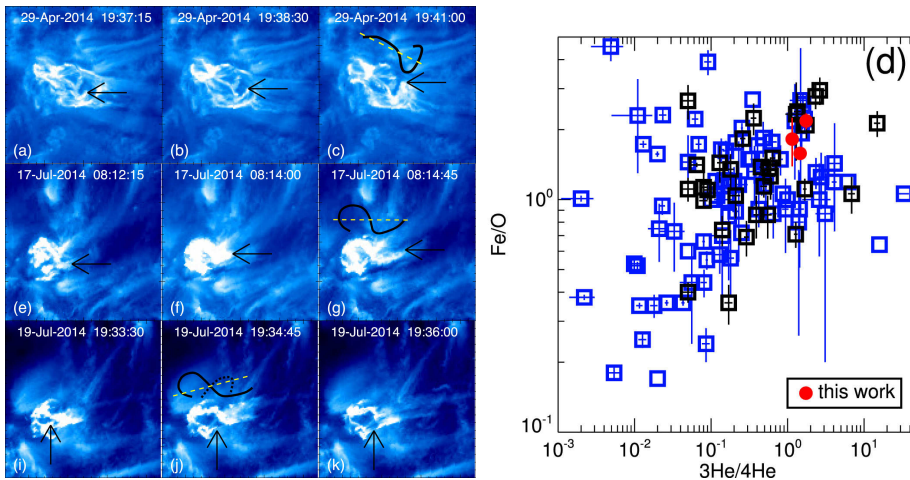


Fig. 2: (Left) STEREO-A EUV 171 Å images of the helical jet evolution in ^3He -rich SEP events on 2014 April 29, 2014 July 17, and 2014 July 19. (Right) Fe/O vs. $^3\text{He}/^4\text{He}$ for events in the left panel (red circles) and all (109) previously reported ^3He -rich SEP events (blue and black squares) at the energy $\sim 0.1\text{--}2$ MeV nucleon⁻¹. Adapted from Bučík et al. (2018b).

et al. 2020), with a high-altitude extension in white-light coronagraphs as narrow coronal mass ejections (CMEs) (Kahler et al. 2001; Wang et al. 2006; Reames et al. 2014b; Wang et al. 2012, 2016; Bronarska et al. 2018). The events with higher ^3He enrichment are coupled with narrow CMEs with low speeds much more strongly than events with lower enrichment (Reames et al. 2014b). Several events, however, show only an amorphous EUV brightening without a jet that is surmised to be an instrument resolution issue (e.g., Wang et al. 2006) and perhaps a projection effect. Jets result from magnetic reconnection between field lines open to interplanetary space and emerging magnetic flux (Shibata et al. 1992) or erupting mini-filament (Canfield et al. 1996; Sterling et al. 2015). Thus, an association of ^3He -rich SEPs with jets implies an ion acceleration mechanism related to magnetic reconnection (Reames 2002).

Using high-resolution imaging observations, the standard and erupting (or blowout) jet dichotomy (Moore et al. 2010) has now started to be addressed in ^3He -rich SEP events (Kahler et al. 2015; Bučík et al. 2018b; Wiedenbeck et al. 2020). It is thought that blowout jets involve more complex reconnection processes than standard, straight jets. A twisted flux rope at the jet source, carried by a mini-filament, has been considered as a triggering mechanism for blowout jets. The events with high enrichments in both ^3He and heavy ions including Fe are associated with blowout jets with helical structure and cool mini filaments at the base of the jets (Mason et al. 2016; Innes et al. 2016; Bučík et al. 2018b). The jets in these events have shown an unwinding motion. Figure 2 presents an example of helical jets in three ^3He -rich SEP events that show high ^3He and Fe enrichments. The unwinding motions in helical jets have been related to the generation/propagation

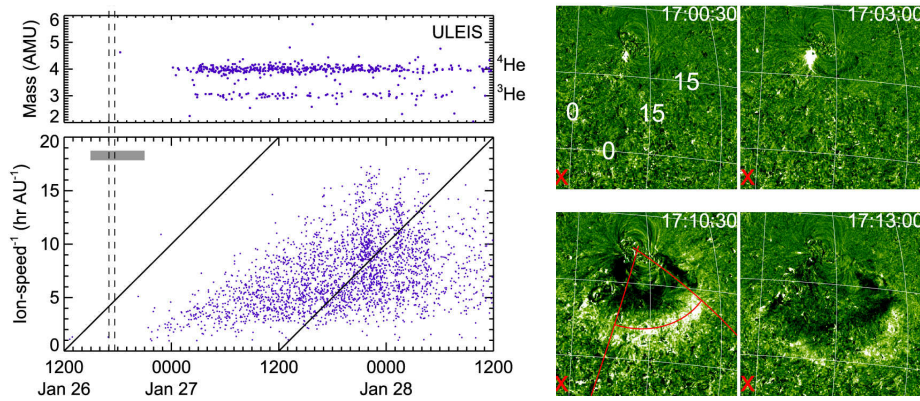


Fig. 3: (Left) The 2010 January 26 ³He-rich SEP event measured on ACE. Blue dots represent 0.4–10 MeV nucleon⁻¹ ions in the mass range 2–6 amu (upper panel) and 0.03–10 MeV nucleon⁻¹ ions in the mass range 10–70 amu (lower panel). Dashed vertical lines mark GOES X-ray B3.2 and B6.7 flares. (Right) STEREO-A 195 Å running difference images around the source AR 11042 on 2010 January 26. Red crosses indicate magnetic foot-points of ACE. During the event, ACE and STEREO-A were angularly separated by 65°. Adapted from Bučík et al. (2015b).

of (torsional) Alfvén waves (e.g., Liu et al. 2011; Lee et al. 2015) which in turn can play a role in ion acceleration (see Section 9).

5 EUV waves

Surprisingly, jets in many ³He-rich events are accompanied by large-scale propagating EUV waves (Bučík et al. 2015b, 2016a; Nitta et al. 2015). Figure 3 shows the 2010 January 26 ³He-rich SEP event with the EUV wave that started as a jet. Though the nature of the EUV waves has been controversial, presently it is believed that they are true magnetosonic waves (see Warmuth 2015, for a review). If EUV waves steepen to shocks, they may affect the energetic ion production in ³He-rich events (Bučík et al. 2016b). However, half of the EUV waves in these events are accompanied by slow CMEs ($\lesssim 300 \text{ km s}^{-1}$). Reames (2019a,b) have suggested that events associated with fast narrow CMEs may involve CME-driven shock reacceleration of ions from magnetic reconnection. There is a tendency for ³He-rich events with jets to have a rounded ³He and Fe spectra towards low energies and for events with coronal waves to have a power-law spectra (Nitta et al. 2015; Bučík et al. 2016b). It has been suggested that rounded spectra arise from a primary mechanism of ³He (Fe) enrichment and power laws involve a further stage of acceleration (Mason et al. 2000, 2002b). It is presently unclear whether broad longitudinal distribution (Wiedenbeck et al. 2013; Nitta et al. 2015; Bučík et al. 2016a; Zhang and Zhao 2017) or delayed ion injection (Wang et al. 2016) measured in several ³He-rich events may be related to EUV waves. We note that all wide-spread ³He-rich events reported by Wiedenbeck et al. (2013) were found

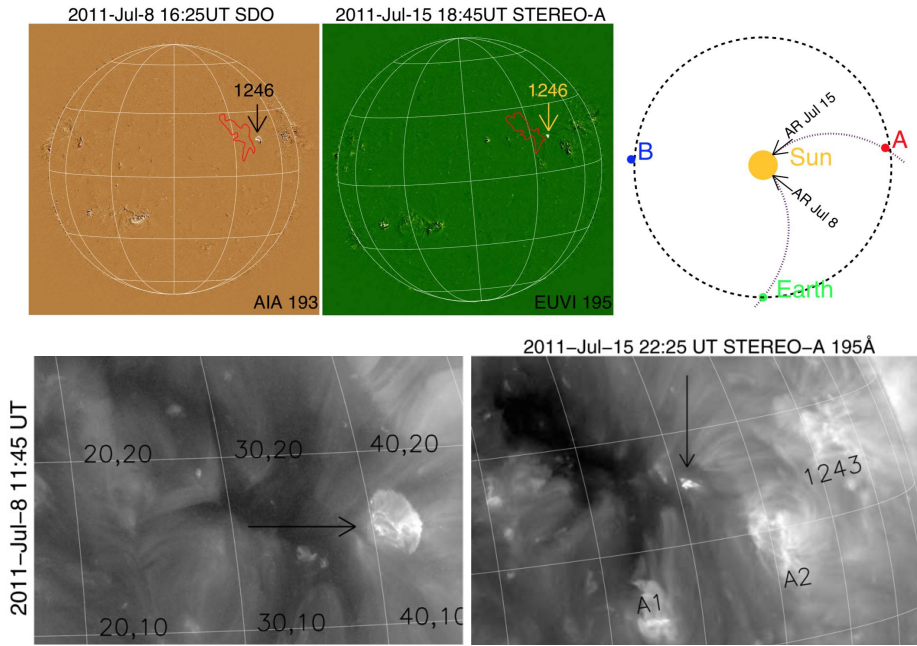


Fig. 4: (Top) EUV running difference images of the solar disk (left, middle); the location of the spacecraft and the source AR on July 8 and July 15 (right). Arrows point to the long-lived ^3He -rich SEP source AR11246 at the boundary of the coronal hole (red contour). The ^3He -rich SEP events from AR11246 were measured on 2011 July 9 by ACE and on 2011 July 16 by STEREO-A. (Bottom) EUV images of a flare/jet from AR11246 in the 2011 July 9 and 2011 July 16 events. Adapted from Bučík et al. (2014, 2015a).

to be accompanied by coronal waves in their source flare (Bučík et al. 2016a; Nitta et al. 2015).

6 Long-lived sources

Measurements with single spacecraft have shown recurrent ^3He -rich SEP events associated with the same source region over relatively short time (~ 1 – 2 day) periods (Reames and Stone 1986; Mazur et al. 1996; Mason et al. 1999, 2000; Wang et al. 2006; Pick et al. 2006; Chen et al. 2015) presumably due to loss of the magnetic connection to the flare site. Multipoint observations with angularly separated spacecraft have shown that a solar source may produce ^3He -rich SEP events at least for a quarter of a solar rotation (see Figure 4; Bučík et al. 2013a, 2014, 2015a). This indicates that more persistent conditions for ion acceleration may exist in ^3He -rich SEP sources (Wang et al. 2006; Pick et al. 2006; Bučík et al. 2014). Note, multi-day periods of the nearly continuous presence of energetic ^3He have been reported around the time of solar maximum often with no individual ^3He -rich events resolved (Mason 2007). Such long periods have been interpreted as

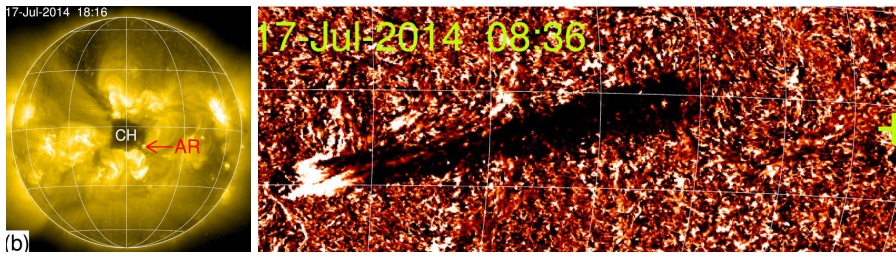


Fig. 5: (Left) STEREO-A 284 Å EUV image of the source AR on the border of a coronal hole for the STEREO-A 2014 July 17 ^3He -rich SEP event. It appears that the coronal hole is an extension of a polar coronal hole through a narrow corridor. (Right) STEREO-A 304 Å EUV running difference image showing a jet with significant non-radial expansion toward the STEREO-A magnetic foot-point (green plus). Adapted from [Bučík et al. \(2018b\)](#).

a combination of continuous emission of energetic ^3He ions and their confinement in interplanetary magnetic field structures ([Kocharov et al. 2008](#)).

7 Photospheric source

The underlying photospheric magnetic field in ^3He -rich SEP sources is generally unknown and has been rarely addressed ([Innes et al. 2016](#)). In their pioneering work, [Kahler et al. \(1987\)](#) have reported the event associated flares close to sunspots, in old spotless regions or bright plage regions with no flares. In further investigations, several ^3He -rich events were found with jets from small active regions at (near-equatorial) coronal hole boundaries ([Wang et al. 2006](#); [Bučík et al. 2013a, 2014, 2015a, 2018b](#)) where magnetic field lines open to the heliosphere. Indeed, ^3He -rich SEP events tend to be detected just before the fast wind ([Zwickl et al. 1978](#); [Mazur et al. 1996](#); [Kocharov et al. 2008](#); [Bučík et al. 2013b](#)) indicating the source active regions are west of coronal holes ([Mazur et al. 1996](#)). Figure 5 shows a jet with significant longitudinal extension from a small, compact active region at the coronal hole boundary for the 2014 July 17 ^3He -rich SEP event. A plage region ([Chen et al. 2015](#); [Bučík et al. 2015a](#)) from dispersed sunspots or newly emerged active regions can also be the source of ^3He -rich jets. So far only one event has been reported arising directly from a sunspot jet ([Nitta et al. 2008](#)).

Recently, rare, very high energy ($>10\text{ MeV nucleon}^{-1}$) ^3He -rich SEP events were associated with jets from the edge of large and complex sunspots ([Bučík et al. 2018a,c, 2019 in preparation](#)). The energy for extensive ion acceleration in these events may originate in the strong magnetic fields of large sunspots and/or from the complexity of the Sun's surface magnetic field (like shearing motions that may accumulate free energy). An example of such an event is shown in Figure 6. Earlier work ([Torsti et al. 2002](#); [Kocharov and Torsti 2003](#); [Torsti et al. 2003](#)) has suggested that high energy ^3He -rich SEPs may be due to re-acceleration in coronal shocks. However, in the above-mentioned recent events no type II-radio bursts, a coronal shock signature, were observed.

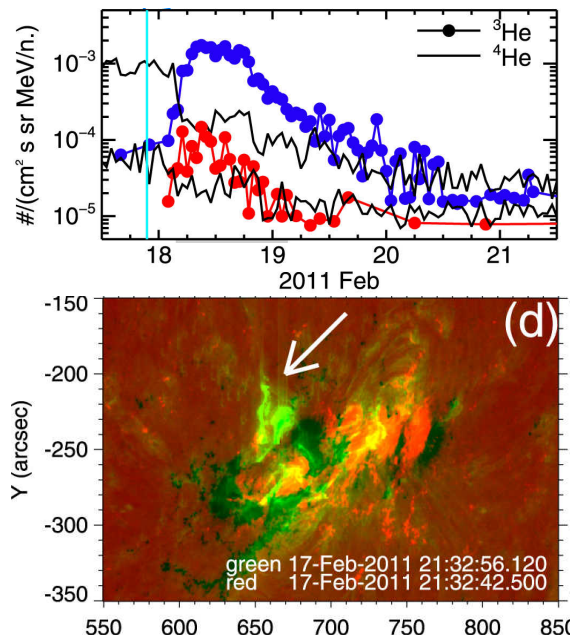


Fig. 6: (Top) The 2011 February 18 ${}^3\text{He}$ -rich SEP event measured on ACE at $5.2\text{ MeV nucleon}^{-1}$ (blue) and $10.5\text{ MeV nucleon}^{-1}$ (red). The solid vertical line marks the event associated C1.1 X-ray flare. (Bottom) Two-color composite image of the solar source for the 2011 February 18 event - helical jet from the boundary of the most complex and large sunspot in the solar cycle 24. Green corresponds to SDO/AIA 304 \AA and red to SDO/HMI line-of-sight magnetic field. Adapted from Bučík et al. (2018c).

8 Temperature

The probable temperature of the source plasma that is accelerated in ${}^3\text{He}$ -rich SEP events is cooler ($2.5\text{--}3.2\text{ MK}$; Reames et al. 2014b, 2015) than typical flare temperatures ($>10\text{ MK}$). It is deduced from the measured ion abundance enhancement pattern and theoretical dependence of equilibrium ionization states on temperature (Reames et al. 1994; Mason et al. 2004). Abundances of ions such as ${}^4\text{He}$, ${}^{12}\text{C}$, ${}^{14}\text{N}$, and ${}^{16}\text{O}$ are unenhanced in ${}^3\text{He}$ -rich events, while heavier species like ${}^{20}\text{Ne}$, ${}^{24}\text{Mg}$, ${}^{28}\text{Si}$ show enhancement. This suggests that C, N, O are fully ionized as ${}^4\text{He}$ but Ne, Mg, Si are only partially stripped. This can happen in a temperature range of $\sim 2.5\text{--}3.2\text{ MK}$. Note that several events have been reported with enhanced ${}^{12}\text{C}$, ${}^{14}\text{N}$ suggesting temperatures $0.5\text{--}1.5\text{ MK}$ (Mason et al. 2002a, 2016). These temperatures may indicate that ions are accelerated very early (Mason et al. 2016) and/or they are accelerated on open field lines where heating is minimal (Reames et al. 2015). More direct determination of the source temperature in ${}^3\text{He}$ -rich SEP events can be obtained from measurements of Fe charge states at low energies ($<100\text{ keV nucleon}^{-1}$; Kocharov et al. 2000; Kovaltsov et al. 2001). DiFabio et al. (2008) have obtained temperatures in the range of $1.3\text{ to }3\text{ MK}$ using low-energy Fe measurements in several ${}^3\text{He}$ -rich SEP events.

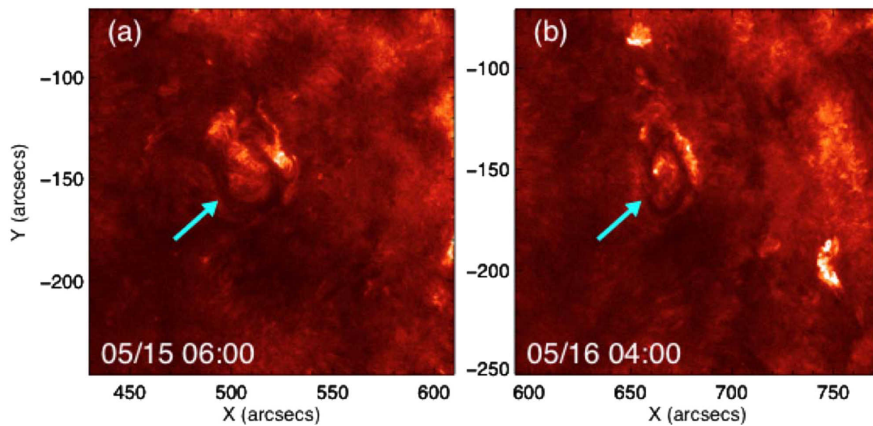


Fig. 7: SDO/AIA 304 Å images of the solar region for the 2014 May 16 ^3He -rich SEP event. The blue arrow shows a ring of cooler material 10 hr (panel a) and 15 minutes (panel b) before the jet. Adapted from [Mason et al. \(2016\)](#).

The presence of cool material in the form of a mini-filament (see Figure 7) may be required for acceleration of lighter species (C, N), as has been recently reported in the sources of ^3He -rich SEP events with large ^3He and Fe enrichments ([Mason et al. 2016](#); [Innes et al. 2016](#); [Bućik et al. 2018b](#)). Fairly low temperatures (0.1–0.6 MK) are required to produce observed heavy-ion enhancements in a new mechanism based on the charge per mass (Q/A) dependence of Coulomb energy losses below the Bragg peak ([Mason and Klecker 2018](#)). However, in a more complete treatment, combining Q/A dependent Coulomb losses with Q/A dependent acceleration, a similar Q/A dependence of heavy-ion abundance enhancements can be obtained, with temperatures of ~ 1 MK ([Kartavykh et al. 2008, 2020](#)). The source temperature ~ 2 MK determined with the Differential Emission Measure method using SDO EUV observations has been reported for one ^3He -rich SEP event ([Chen et al. 2018](#)). In early studies, an abundance enhancement increase with soft X-ray temperature (in the range 10–16 MK) has been shown ([Reames 1988](#)) for some heavy elements (C, Mg, Si, S, Fe). The origin of the reported dependencies remains unclear if many of these species are fully stripped ([Reames 1988](#)). Why SEP abundances should correlate with the X-ray temperature of closed heated regions near the source? Limited statistics and possible wrongly associated events do not seem to explain the fairly high correlations. Could wave energy from hot regions affect nearby SEPs? [Reames \(1990\)](#) has suggested that plasma waves escaping from a closed X-ray region ([Sprangle and Vlahos 1983](#)) accelerate ions in impulsive SEP events. The $^3\text{He}/^4\text{He}$ ratio showed no correlation with temperature ([Reames et al. 1988](#)).

9 Acceleration

Various processes have been proposed to explain the anomalous abundances of ^3He -rich SEPs (see review by [Miller 1998](#)). These processes address ^3He and heavy-ion acceleration separately. They, however, must fit together in some way, even

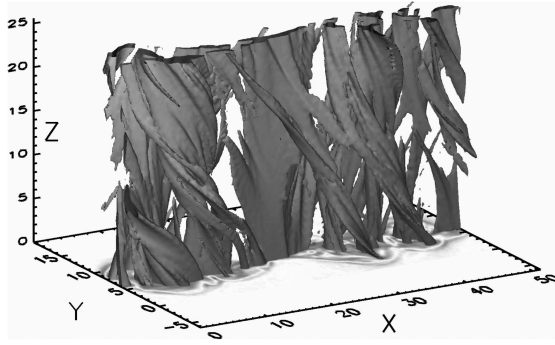


Fig. 8: Isosurface of the electron current density that exhibit filamentary structure in the 3D simulation (from Dahlin et al. (2015)).

though the magnitude of these enhancements is uncorrelated. Most models involve ion-cyclotron resonance with plasma waves. The models of cascading Alfvén waves may account for heavy-ion acceleration (Miller 1998; Zhang 2004) where ions with low Q/A are accelerated with a faster rate (Eichler 2014; Kumar et al. 2017). This is qualitatively compatible with measured enhancements of heavy ions in ^3He -rich events (Mason et al. 2004; Reames and Ng 2004). The models assume that waves generated at long wavelengths during the reconnection by relaxation of twisted non-potential magnetic fields, cascading toward shorter length scales, resonate with ions of increasing gyro-frequency or Q/A (Miller 1998). The models of ^3He acceleration involve plasma waves generated around the ^3He cyclotron frequency (Fisk 1978; Temerin and Roth 1992; Liu et al. 2006). These waves are assumed to be generated by an electron current, energetic electron beams, or via coupling with low-frequency Alfvén waves. It is remarkable that the efficient acceleration of ^3He by ion-cyclotron resonance has been recently measured in nuclear fusion devices (Kazakov et al. 2017).

Besides models based on cyclotron resonance, some other (non-wave) mechanisms have been proposed. These include ion fractionation by reconnection outflows followed by Fermi acceleration on multiple magnetic islands (Drake et al. 2009; Kramoliš et al. 2019 in preparation) and fractionation by magnetic helicity-driven DC electric fields (Holman 1995; Fleishman and Topygin 2013) followed by cyclotron resonance. In the former model, a production rate is scaled by Q/A as a power-law (Drake et al. 2009) that is consistent with measurements. The magnetic islands have been observed in the reconnection sites through direct imaging and a temperature analysis (Li et al. 2016). The model with helicity-driven DC electric field (Fleishman and Topygin 2013) predicts common enrichment of ^3He and Fe, reported in events with helical jets (Mason et al. 2016; Bučík et al. 2018b).

Recent 3D simulations have shown that reconnection in the corona is intrinsically turbulent (Daughton et al. 2011). The resulting turbulent magnetic structures, that represent magnetic islands in 2D, enhance electron (Dahlin et al. 2015) as well as ion (J. F. Drake, private communication) acceleration, facilitating particle transport. These stochastic magnetic structures are illustrated in Figure 8. The observed helical morphology in ^3He -rich jets may be a signature of these turbulent structures or torsional Alfvén waves on large scales.

Earlier work speculated that abundance variations in source material may affect the anomalous composition of ^3He -rich SEPs (Mason et al. 1986; Reames et al. 1990). Winglee (1989) has suggested that variations in the source material can be discernable with EUV spectral line observations. Small field-of-view of EUV spectrographs may be a limiting factor for systematic investigation of EUV lines in ^3He -rich SEP sources, but the intentional pointing to the magnetically connected flares may be helpful (Bučík et al. 2018a). For example, proposals can be submitted for coordinated observations of the EUV Imaging Spectrometer (EIS) on Hinode and Interface Region Imaging Spectrograph (IRIS) to investigate jets in ^3He -rich SEP sources (<https://hinode.msfc.nasa.gov/hops.html>).

10 Summary

Discovered more than 50 years ago, ^3He -rich SEP events are still poorly understood. It is mainly because of their low intensities, short duration, association with minor flares, and the requirement for a relatively accurate magnetic connection to a small size source on the Sun. Furthermore, energetic ions in ^3He -rich events do not show flare signatures as energetic electrons through the hard X-ray bremsstrahlung or radio emissions. Signatures of ion acceleration in EUV spectral lines in large X-ray flares have been recently investigated (e.g., Jeffrey et al. 2016) and may find application for sources of ^3He -rich SEPs.

We expect that new missions at a close distance of the Sun, Parker Solar Probe (launched in 2018) and Solar Orbiter (launched in 2020) will revolutionize our view on processes responsible for ion acceleration in ^3He -rich SEP events. For example, observations from an unprecedentedly close distance (~ 10 – 35 solar radii; compare 215 solar radii from 1 au) to the Sun will remove uncertainties due to interplanetary propagation effects and magnetic connection. Such observations may reveal new solar sources of ^3He -rich SEPs. One such source may be a local acceleration of ^3He -rich SEPs in the solar wind (J. F. Drake, private communication).

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