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Observations of Extremely ^{3}He-Rich Solar Energetic Particle Events from *Parker Solar Probe*

R. A. Leske,[a,*] **E. R. Christian,**[b] **C. M. S. Cohen,**[a] **A. C. Cummings,**[a] **A. J. Davis,**[a] **G. A. de Nolfo,**[b] **M. I. Desai,**[c,d] **J. Giacalone,**[e] **M. E. Hill,**[f] **A. W. Labrador,**[a] **D. J. McComas,**[g] **R. L. McNutt Jr.,**[f] **R. A. Mewaldt,**[a] **D. G. Mitchell,**[f] **J. G. Mitchell,**[b] **J. S. Rankin,**[g] **N. A. Schwadron,**[g,h] **T. Sharma,**[g] **M. M. Shen,**[g] **J. R. Szalay,**[g] **M. E. Wiedenbeck,**[i] **A. Vourlidas,**[f] **S. D. Bale,**[j] **M. Pulupa,**[j] **J. C. Kasper,**[k] **D. E. Larson**[j] **and P. Whittlesey**[j]

[a] *California Institute of Technology, Pasadena, CA 91125, USA*
[b] *NASA/Goddard Space Flight Center, Greenbelt, MD 20771, USA*
[c] *Southwest Research Institute, San Antonio, TX 78228, USA*
[d] *University of Texas at San Antonio, San Antonio, TX 78249, USA*
[e] *University of Arizona, Tucson, AZ 85721, USA*
[f] *Johns Hopkins University Applied Physics Laboratory, Laurel, MD 20723, USA*
[g] *Department of Astrophysical Sciences, Princeton University, Princeton, NJ 08544, USA*
[h] *University of New Hampshire, Durham, NH 03824, USA*
[i] *Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA*
[j] *University of California at Berkeley, Berkeley, CA 94720, USA*
[k] *University of Michigan, Ann Arbor, MI 48109, USA*

E-mail: ral@srl.caltech.edu

Since its launch in 2018, the Integrated Science Investigation of the Sun (IS⊙IS) instrument suite on *Parker Solar Probe* has observed numerous periods of ^{3}He-rich solar energetic particle (SEP) events. Notable among them are some very small events that occurred on 21 January 2021 and 30 May 2022, in both cases when *Parker* was within 0.2 AU of the Sun. In these events the ^{3}He/^{4}He ratio was greater than 10 at ∼1 MeV/nucleon but rapidly decreased with increasing energy since ^{3}He had softer spectra than ^{4}He. Although unusual, similar extreme enrichments of ^{3}He have occasionally been observed at 1 AU in other events. The events seen by *Parker* were anisotropic, had velocity dispersion yielding inferred pathlengths longer than expected for scatter-free transport along a nominal Parker spiral, and were associated with type III radio emission detected by *Parker*/FIELDS. We present the *Parker* observations of the time profiles, spectra, composition, velocity dispersion, and anisotropies of these events and compare them with previous ^{3}He-rich SEP events detected much farther from the Sun.

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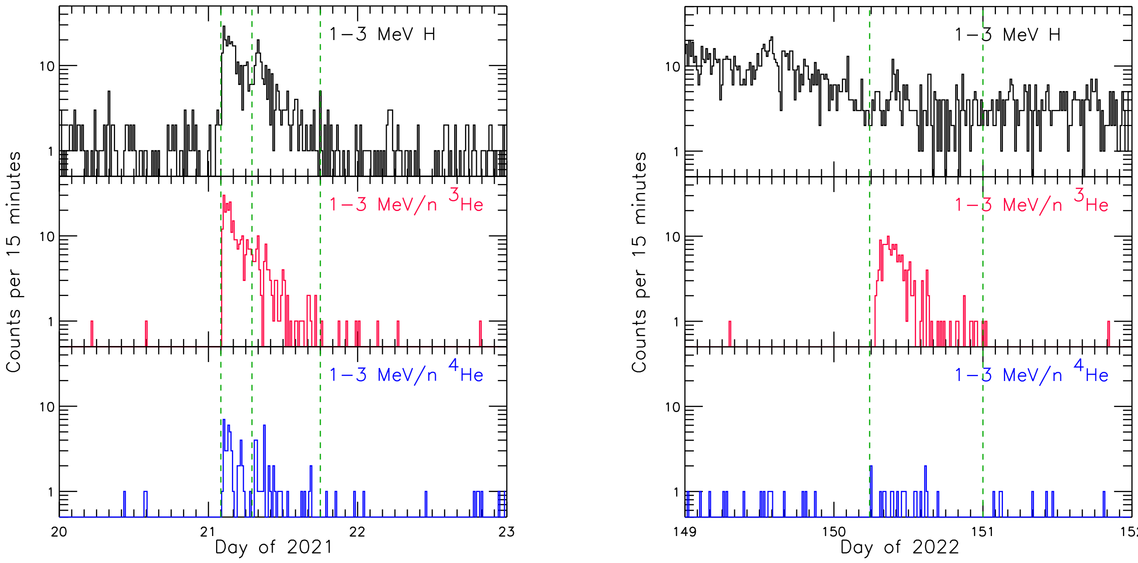

Figure 1: 15-minute averaged count rates of 1-3 MeV/nucleon H (*top panels*), ^{3}He (*middle panels*), and ^{4}He (*bottom panels*) from EPI-Hi during the 21 January 2021 events (*left panels*) and the 30 May 2022 event (*right panels*). *Dashed vertical lines* mark the time boundaries used in producing the spectra in Figure 3.

1. Introduction

In August 2018, the *Parker Solar Probe* mission was launched to study the physical processes of the near-Sun environment [1], including those responsible for the acceleration and transport of solar energetic particles (SEPs). On *Parker*, SEP spectra, composition, and anisotropies are measured by the Integrated Science Investigation of the Sun (IS⊙IS), a suite comprising two Energetic Particle Instruments, EPI-Lo and EPI-Hi [2]. EPI-Lo measures particles from ~20 keV/nucleon to several MeV/nucleon using the time-of-flight versus energy technique [2, 3]. EPI-Hi uses the dE/dx versus residual energy method in a set of three silicon solid-state detector telescopes (called LET1, LET2, and HET) that together cover an energy range of ~1-200 MeV/nucleon [2, 4]. All of the EPI-Hi data used in this present report are from the double-ended, cylindrical LET1 telescope. The full field of view of each end of this telescope is a 90°-wide cone lying in the spacecraft orbital plane, with one aperture (LET-A) pointed 45° west of the Sun-spacecraft line and the opposite end (LET-B) pointed 135° east of the Sun during solar encounters.

Now that solar activity has been increasing in solar cycle 25, many SEP events both large and small have been observed by IS⊙IS (e.g., [5–8]). Here we describe several SEP events that were distinguished by being extremely rich in ^{3}He and detected very close to the Sun. In particular, we discuss a pair of small SEP events detected on 21 January 2021 when *Parker* was traveling from 0.18 to 0.20 AU outbound from Encounter 7, and an even smaller event seen on 30 May 2022 between 0.16 and 0.13 AU when *Parker* was inbound to Encounter 12.

2. Observations

Figure 1 shows the time profiles of 1-3 MeV/nucleon H, ^{3}He, and ^{4}He for the periods discussed here, using LET1 pulse-height event data. On 21 January 2021, the H time profile (and perhaps

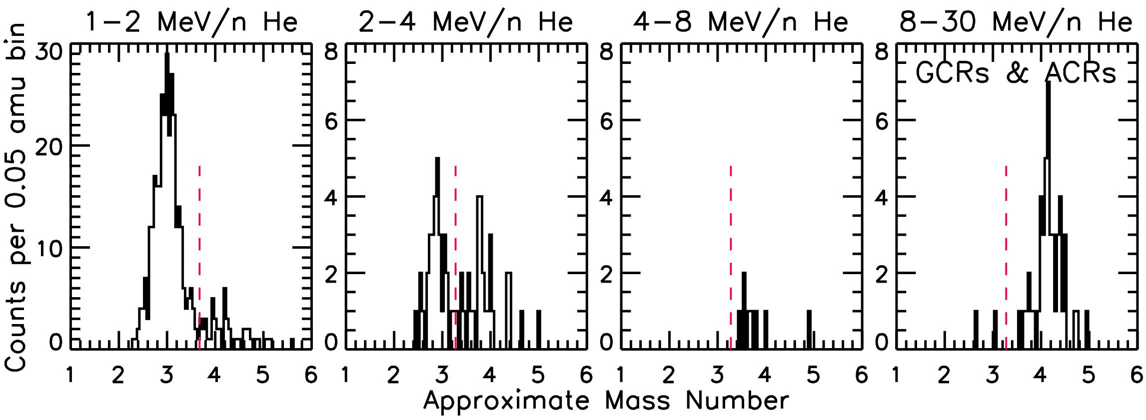

Figure 2: He mass histograms from LET1 pulse-height data integrated over both 21 January 2021 events (02:00-18:00) in 4 energy bins as indicated. *Dashed vertical lines* mark the boundaries between mass 3 and mass 4 used to construct the isotope spectra in Figure 3.

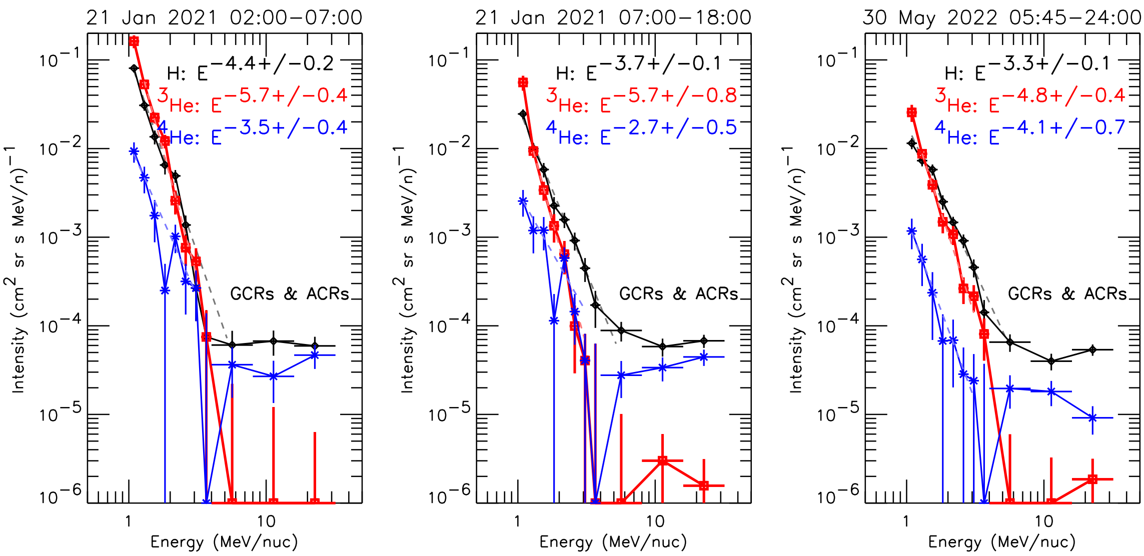

Figure 3: Spectra for H (*black*), ^{3}He (*red*) and ^{4}He (*blue*) during the 3 event periods indicated. In each case, for all these species, the spectra are dominated by GCRs and ACRs above ~5 MeV/nuc. Power-law fits to the lower energies are shown by *dashed lines*, with the fit spectral indices indicated.

the others) suggests the presence of two separate injections; associated type III bursts and changes in the anisotropies, as we discuss later, support this assessment. In the 30 May 2022 event, H is dominated by protons from the decay phase of an earlier SEP event, and the increase in ^{4}He is barely detectable, but a small event is obvious in ^{3}He. In both these periods elemental He was similar in intensity to H, but most of this He was in the form of ^{3}He. EPI-Hi did not detect electrons or heavier ions in any of these tiny events.

Mass histograms of He summed over the two 21 January 2021 events are shown for four energy bands in Figure 2. The ^{3}He/^{4}He ratio varied greatly with energy. At 1-2 MeV/nucleon the SEP event dominated, and He was almost entirely ^{3}He, with a mass resolution of σ_M~0.25 amu. Above 8 MeV/nucleon He at this time was almost entirely due to galactic cosmic rays (GCRs) and

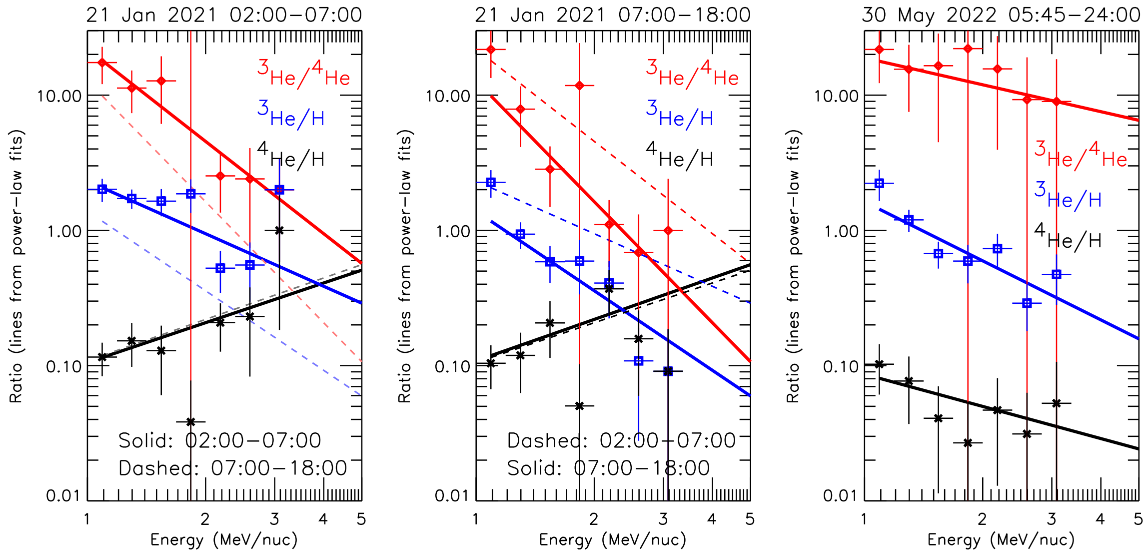

Figure 4: Abundance ratios of ^{3}He/^{4}He (*red*), ^{3}He/H (*blue*), and ^{4}He/H (*black*) as a function of energy during the 3 events discussed here. *Solid lines* show ratios obtained from the fits in Figure 3. For the two events on 21 January 2021, *dashed lines* show the fit from the other event, to illustrate the different ^{3}He abundance between the two.

anomalous cosmic rays (ACRs), and at these energies was nearly all ^{4}He.

Combined LET-A and LET-B spectra in the spacecraft frame are shown for H, ^{3}He, and ^{4}He in Figure 3, integrated over each of the three events. These events were very small, with H and He disappearing into the GCR and ACR backgrounds by ~5 MeV/nucleon (note that GCR and ACR intensities this close to the Sun are fairly similar to those at 1 AU). Power-law fits to the spectra below 5 MeV/nucleon are shown, with the spectral indices as indicated. Although GCR and ACR backgrounds were not subtracted, these fits are dominated by the lower energies, where intensities were 2-3 orders of magnitude above background. The spectra were rather soft, with the ^{4}He spectra significantly harder than those for ^{3}He in the January 2021 events and marginally so for the May 2022 event.

Because the spectra were different for the different species, the composition was energy-dependent, as shown in Figure 4. In all three events, the ^{4}He/H ratio showed the least energy dependence. In the two January 2021 events the ^{4}He/H ratio was nearly identical, while the ^{3}He abundance varied between the two events, and the ^{3}He/^{4}He ratio dropped by 2 orders of magnitude over a factor of only 5 in energy in the second 21 January event. The ^{3}He/H and ^{4}He/H ratios shown for the 30 May 2022 event should be regarded as lower limits, since no correction has been applied for the pre-event H background seen in Figure 1. All three events were so enriched in ^{3}He that at 1 MeV/nucleon the event-averaged ^{3}He intensity exceeded that of protons, and ^{3}He/^{4}He was >10.

Time profiles in the LET-A and LET-B apertures separately are shown in Figure 5. Particles coming from the Sun exceeded those flowing back towards the Sun by about an order of magnitude (for H) at the onset of both January 2021 events, but by a lesser amount in the 30 May 2022 event. There may be some suggestion of anisotropy just before the apparent onset of the May event, but the statistical significance is marginal.

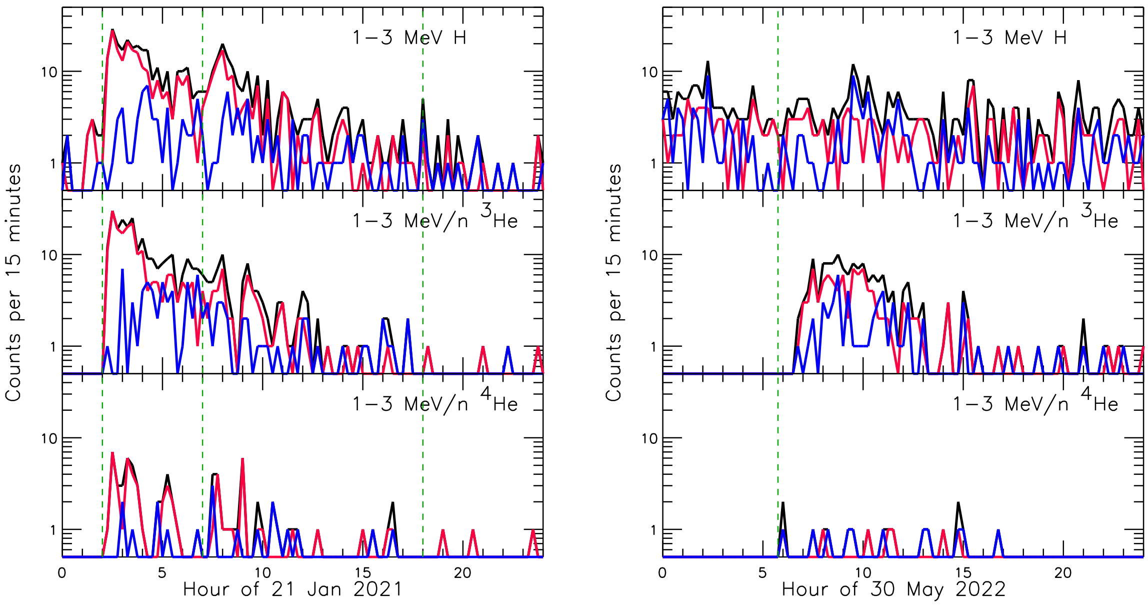

Figure 5: Similar to Figure 1, except distinguishing the LET1 aperture by color: *red* indicates counts in LET-A (particles coming from the Sun), *blue* in LET-B (flowing towards the Sun), and *black* is the sum of both LET-A and LET-B.

Velocity dispersion in the first of the two 21 January 2021 events is evident in Figure 6. As is often the case (e.g., [6]), the apparent pathlength obtained from the onset edge of the first arriving particles is considerably longer than expected if the particles traveled at 0° pitch angle along a nominal Parker spiral field line. Possible reasons could include a non-Parker spiral field configuration, scattering, field line random walk [9], or delayed release of lower energy particles. Intensities in the 30 May 2022 event were so much lower that any velocity dispersion and the inferred length of the path are highly uncertain.

Dynamic radio spectra from the *Parker*/FIELDS Radio Frequency Spectrometer [10, 11] are shown in Figure 7. Both the 21 January 2021 events were associated with pairs of type III radio bursts. The lack of clear velocity dispersion in the tiny 30 May 2022 event makes the onset time uncertain, but based on the time profiles in Figure 1 and Figure 5, particles started arriving by ~06:00. The type III emission around 05:20 in Figure 7 is the most likely radio counterpart to this event, although several in the previous hour may also be possible; there were no additional type III events detected between ~05:30 and 10:00.

3. Discussion

The solar source region of the January 2021 events is highly uncertain. *Parker* was at 135° Carrington longitude at 02:00 on 21 January 2021, 120° west of Earth, thus most of the solar hemisphere facing *Parker* was unobservable from near-Earth assets (e.g., *STEREO*, *SDO*, etc.). Although *Solar Orbiter* (*SolO*) was only ~30° west of *Parker*, all of its instruments were off at the time. The only known active region in *Parker*'s hemisphere was AR12796 at 89° longitude, but this is unlikely to have been the source as it had decayed to a plage and had produced no flares during its

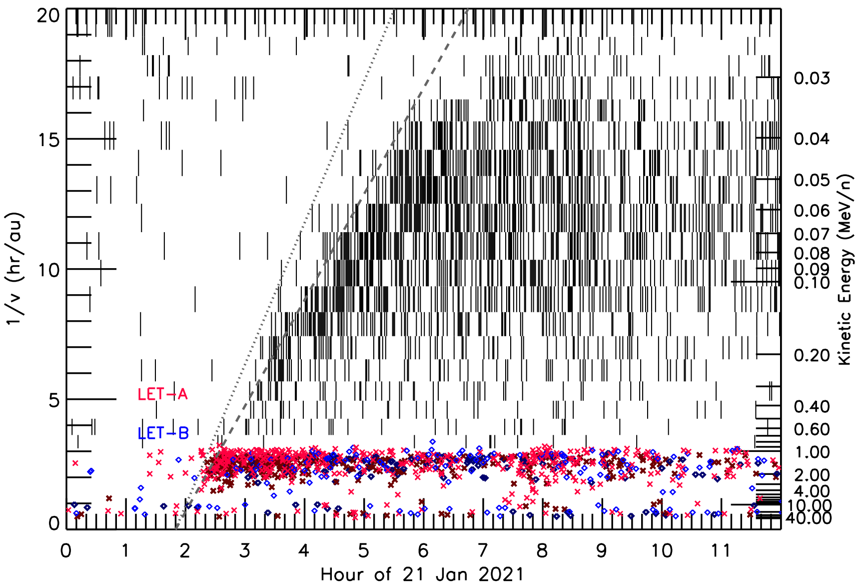

Figure 6: The reciprocal of the particle velocity versus arrival time for H (*lighter colors*) and He (*darker colors*) in LET-A (*red*) and LET-B (*blue*) using pulse-height data in LET1. *Black line segments* indicate H from the EPI-Lo time-of-flight rates, averaged over the EPI-Lo apertures (omitting those punctured by dust grains). The *dashed line* shows the onset edge that approximately matches the data, corresponding to a release time of 1:50 and a pathlength of 0.246 au, while the *dotted line* shows where the onset edge would be with the same release time but the pathlength of a nominal Parker spiral with the ambient 225 km/s solar wind speed.

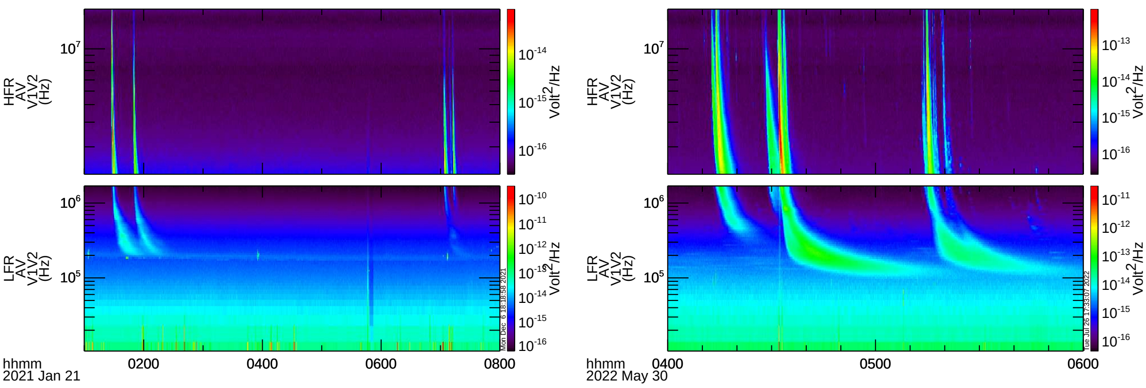

Figure 7: Type III radio emission observed by FIELDS on *Parker* during the 21 January 2021 SEP events (*left panel*) and near the likely onset time (see text) of the 30 May 2022 event (*right panel*).

transit of the Earth-facing disk. *STEREO*/SECCHI observed a coronal mass ejection (CME) from over its east limb around the time of the events; if associated with the SEPs, this suggests a source at ~170-220° longitude, west of *Parker*. However, small ^{3}He-rich particle events do not require a CME, and instead are often associated with merely a flare or coronal jet [12, 13], so this CME may be unrelated.

The alignment in the 30 May 2022 event was even less favorable, with *Parker* separated from Earth by 150° (and from *STEREO-A* by 176°, almost exactly on the opposite side of the Sun).

However, *SolO* was only 17° from *Parker* with its instruments operating. Uncertainty in the onset timing in this tiny event, together with the cadence of *SolO* EUI observations, makes the search for a source challenging, and more work is needed. The SEP event was not detected by the Energetic Particle Detector (EPD) on *SolO*. This may be due to the longitudinal separation between the *SolO* and *Parker* magnetic footpoints of ∼50°, or due to the much greater distance of *SolO* from the Sun (0.92 AU compared with 0.16 AU for *Parker*). If the peak intensities fell with helioradius R as R^{-3} [14], H and He would have been undetectable at *SolO* even if it were magnetically well-connected to *Parker*. Indeed, all three of the very small near-perihelion events discussed here would have gone unnoticed at 1 AU, suggesting that such events may be rather common and could constitute a source of seed particles for acceleration in larger SEP events or account for the frequently observed diffuse MeV/nucleon ^{3}He ions seen near solar maximum [15].

Compared with other events previously reported from *Parker*/EPI-Hi, the ^{3}He/^{4}He ratio of ∼10 in the events discussed here far exceeds that of 0.063±0.016 in the 20-21 April 2019 ^{3}He-rich event [5]. Also, although the He/H elemental ratio in small events can be highly variable (see, e.g., [7] and discussion therein), a value as high as 1 as seen in all three of the present events (albeit almost entirely due to ^{3}He) is exceptional.

The ^{3}He spectra in these events was softer than the ^{4}He spectra above 1 MeV/nucleon (Figure 3). If the spectra continued as the same power laws down to the lower energies measured by EPI-Lo, the ^{3}He/^{4}He ratio at several hundred keV/nucleon would have been even greater than the value of ∼10 seen at several MeV/nucleon. The sensitivity and mass resolution of EPI-Lo make it unclear if it detected any enrichment of ^{3}He, but it seems definite that ^{3}He did not exceed ^{4}He in EPI-Lo. This suggests that the shapes of the ^{3}He and ^{4}He spectra were different at lower energies, with ^{3}He rolling off below 1 MeV/nucleon as is often seen in ^{3}He-rich events at 1 AU [16].

The ^{3}He/^{4}He ratios in the events discussed here were certainly extreme, but not unique. Events have sometimes been observed at 1 AU which seemed to consist entirely of ^{3}He, with no ^{4}He, H, or electrons detected [17]. Perhaps as solar activity continues to increase, *Parker* may observe more of these events closer to the Sun and help to determine the origin of this peculiar enrichment.

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References

[1] N. J. Fox, M. C. Velli, S. D. Bale, et al., *The Solar Probe Plus Mission: Humanity's First Visit to Our Star*, *Space Sci. Rev.* **204** (Dec., 2016) 7–48.

[2] D. J. McComas, N. Alexander, N. Angold, et al., *Integrated Science Investigation of the Sun (ISIS): Design of the Energetic Particle Investigation*, *Space Sci. Rev.* **204** (Dec, 2016) 187–256.

[3] M. E. Hill, D. G. Mitchell, G. B. Andrews, et al., *The Mushroom: A half-sky energetic ion and electron detector*, *J. Geophys. Res.* **122** (Feb., 2017) 1513–1530.

[4] M. E. Wiedenbeck, N. G. Angold, B. Birdwell, et al., *Capabilities and Performance of the High-Energy Energetic-Particles Instrument for the Parker Solar Probe Mission*, *Proc. 35th Internat. Cosmic Ray Conf. (ICRC2017)* **301** (Jan, 2017) 16.

[5] M. E. Wiedenbeck, R. Bučík, G. M. Mason, et al., *^{3}He-rich Solar Energetic Particle Observations at the Parker Solar Probe and near Earth*, *ApJS* **246** (Feb., 2020) 42.

[6] R. A. Leske, E. R. Christian, C. M. S. Cohen, et al., *Observations of the 2019 April 4 Solar Energetic Particle Event at the Parker Solar Probe*, *ApJS* **246** (Feb., 2020) 35, [arXiv:1912.0338].

[7] C. M. S. Cohen, E. R. Christian, A. C. Cummings, et al., *Parker Solar Probe observations of He/H abundance variations in SEP events inside 0.5 au*, *A&A* **650** (June, 2021) A23.

[8] C. M. S. Cohen, E. R. Christian, A. C. Cummings, et al., *PSP/IS⊙IS observations of the 29 November 2020 solar energetic particle event*, *A&A* **656** (Dec., 2021) A29.

[9] R. Chhiber, W. H. Matthaeus, C. M. S. Cohen, et al., *Magnetic field line random walk and solar energetic particle path lengths. Stochastic theory and PSP/IS⊙IS observations*, *A&A* **650** (June, 2021) A26, [arXiv:2011.0832].

[10] S. D. Bale, K. Goetz, P. R. Harvey, et al., *The FIELDS Instrument Suite for Solar Probe Plus. Measuring the Coronal Plasma and Magnetic Field, Plasma Waves and Turbulence, and Radio Signatures of Solar Transients*, *Space Sci. Rev.* **204** (Dec., 2016) 49–82.

[11] M. Pulupa, S. D. Bale, J. W. Bonnell, et al., *The Solar Probe Plus Radio Frequency Spectrometer: Measurement requirements, analog design, and digital signal processing*, *J. Geophys. Res.* **122** (Mar, 2017) 2836–2854.

[12] R. Bučík, M. E. Wiedenbeck, G. M. Mason, et al., *^{3}He-rich Solar Energetic Particles from Sunspot Jets*, *ApJL* **869** (Dec., 2018) L21, [arXiv:1812.0773].

[13] N. V. Nitta, G. M. Mason, L. Wang, et al., *Solar Sources of ^{3}He-rich Solar Energetic Particle Events in Solar Cycle 24*, *ApJ* **806** (June, 2015) 235, [arXiv:1505.0680].

[14] D. Lario, A. Aran, R. Gómez-Herrero, et al., *Longitudinal and Radial Dependence of Solar Energetic Particle Peak Intensities: STEREO, ACE, SOHO, GOES, and MESSENGER Observations*, *ApJ* **767** (Apr., 2013) 41.

[15] M. E. Wiedenbeck, G. M. Mason, C. M. S. Cohen, et al., *Occurrence of 3He-rich Solar Energetic Particles near Earth and Closer to the Sun*, *Proc. 36th Internat. Cosmic Ray Conf. (ICRC2019)* **36** (July, 2019) 1171.

[16] G. M. Mason, M. E. Wiedenbeck, J. A. Miller, et al., *Spectral Properties of He and Heavy Ions in ^{3}He-rich Solar Flares*, *ApJ* **574** (Aug., 2002) 1039–1058.

[17] G. C. Ho, G. M. Mason, and R. C. Allen, *^{3}He-Rich Solar Energetic Particle Events with No Measurable ^{4}He Intensity Increases*, *Solar Physics* **294** (Mar., 2019) 33.