The Astrophysical Journal, 700:L56–L59, 2009 July 20 doi:10.1088/0004-637X/700/1/L56

SOLAR ENERGETIC PARTICLE ^{3}He-RICH EVENTS FROM THE NEARLY QUIET SUN IN 2007–2008

G. M. Mason[1], N. V. Nitta[2], C. M. S. Cohen[3], and M. E. Wiedenbeck[4]
[1] Johns Hopkins University/Applied Physics Laboratory, Laurel, MD 20723, USA; glenn.mason@jhuapl.edu
[2] Lockheed Martin Solar and Astrophysics Lab., Palo Alto, CA 94304, USA
[3] California Institute of Technology, Pasadena, CA 91125, USA
[4] Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA
Received 2009 April 27; accepted 2009 June 18; published 2009 July 2

ABSTRACT

We have used *Advanced Composition Explorer* instruments to survey the period 2007 March through the end of 2008 for ^{3}He-rich solar energetic particle (SEP) events occurring during near solar minimum conditions. Four events were found, all associated with single solar active regions in the western hemisphere. They all show ^{3}He:^{4}He ratios of a few percent (i.e., $\gtrsim$100 times solar system abundances), low intensities, and spectra extending up to at least 1 MeV nucleon^{-1}. Two events, on 2008 February 4 and 2008 June 16, were devoid of signatures associated with ^{3}He-rich SEPs, namely they lacked associations with energetic electrons and type-III bursts. In addition, there were no clear coronal mass ejections and X-ray flare activity was very low or absent. We take this as evidence that the irreducible requirement for ^{3}He-rich SEPs is a western hemisphere solar active region where magnetic and plasma processes preferentially energize ^{3}He and heavy ions.

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

1. INTRODUCTION

Solar energetic particle (SEP) events with large enrichments of ^{3}He (up to factors of $>10^4$) have been long studied since their elemental and isotopic fractionation properties are evidence of an acceleration mechanism distinct from those operating in large SEP events. ^{3}He-rich SEP events have modest intensities, and are associated with type-III radio bursts, energetic electrons, and enrichments of heavy nuclei up to >200 AMU (see reviews by, e.g., Kocharov et al. 1984; Reames 1999; Mason 2007).

Many, and perhaps the majority of these events, have no obvious source identification on the Sun (e.g., Kahler et al. 1987). Nevertheless with the availability of advanced instruments on SOHO, the *Advanced Composition Explorer* (*ACE*), TRACE, and *Hinode,* in conjunction with ground-based measurements, a number of ^{3}He-rich events have recently been identified with western hemisphere solar active regions producing type-III bursts and jets. These regions tend to be located near small coronal holes whose open magnetic field lines allow energized particles to escape into interplanetary space. The jet activity is associated with magnetic reconnection between closed and open field lines (Pick et al. 2006; Wang et al. 2006; Nitta et al. 2008).

This recent progress in identifying the solar sources still leaves open key questions about particle acceleration in ^{3}He-rich SEPs. For example, are the ions accelerated in the reconnection region by stochastic turbulence (Fisk 1978; Miller et al. 1996; Zhang 1999; Liu et al. 2006)? Or are the ions accelerated continuously on shrinking magnetic islands that arise from the microphysics of the reconnection process (Drake et al. 2006; Drake et al. 2009)? Do the jets or narrow coronal mass ejections (CMEs) often observed in association with these events play a critical role in acceleration?

Distinguishing amongst these possibilities is difficult during solar active periods when the observational studies have taken place, since at any one time there is a generally solar activity in several sites and erroneous associations may arise (e.g., see the discussion in Rust et al. 2008).

In this Letter we report a survey of ^{3}He-rich SEPs during near solar minimum conditions in 2007–2008, when there is the least possible ambiguity of the solar sources and other activity. Our purpose is to identify the minimum solar activities associated with acceleration of ^{3}He-rich SEPs.

2. OBSERVATIONS

The ion observations reported here were carried out with the Ultra-Low Energy Isotope Spectrometer (ULEIS; Mason et al. 1998) on the *ACE* spacecraft, which was launched into an orbit around the sunward Lagrangian point in 1997. ULEIS is a time-of-flight mass spectrometer covering the energy range ∼0.1–10 MeV nucleon^{-1}. These observations were combined with data from other sources cited in the table and text.

The survey period began in 2007 March and continued through the end of 2008. During the survey period *ACE* instruments observed no ^{3}He-rich SEPs with intensities and velocity dispersion comparable to those routinely observed in the last solar cycle (e.g., Mason et al. 2000; Nitta et al. 2006; Nitta et al. 2008). Rather, we searched for any statistically significant enhancement of ∼0.5 MeV nucleon^{-1} ^{3}He intensities of at least 24 hr duration.

During the survey period there were ∼50 solar active regions, of which four produced ^{3}He-rich periods listed in Table 1. The table lists the time intervals used for computing spectra and key fluences and ratios. The particle events are near the very limits of detection for the instrument, much smaller than typical events previously reported from ULEIS. For example, the ^{3}He fluence in the event of 2007 May 23 is about a factor of 25 lower than the fluence in the 2006 November 17 event studied by Nitta et al. (2008). Only event 4 has the magnetic polarity associated with the new solar cycle.

Figure 1 shows He mass histograms for the four events. Panels (b)–(d) cover the range 0.5–2 MeV nucleon^{-1} used in previous surveys for ULEIS data, while panel (a) uses a lower threshold due to a lack of statistics above 0.5 MeV nucleon^{-1}. The ^{3}He presence at a level of a few percent of ^{4}He clearly identifies these periods, as does the high Fe/O ratio in the three periods where it

Table 1
^{3}He-rich Period Particle and Solar Properties

Event Number	1	2	3	4
^{3}He-rich period start day	2007 May 23[a]	2008 February 4	2008 June 16	2008 November 4[b]
^{3}He-rich interval (day of year)	143.31 – 143.92	35.0 – 37.75[c]	168.9 – 171.9[c]	309.14 – 310.14[d]
^{3}He Fluence × 10[e]	2.9 ± 1.4	7.2 ± 2.3	4.3 ± 1.8	5.0 ± 1.9
Fe Fluence × 10[e]	1.4 ± 0.3	⩽ 0.08	...	1.2 ± 0.3
^{3}He/^{3}He (%)[e]	1.1 ± 0.6	15.9 ± 5.4	4.2 ± 1.7	4.2 ± 1.6
^{4}He/O[e]	411 ± 139	133 ± 62	218 ± 84	172 ± 56
Fe/O[e]	2.3 ± 1.0	∼1[f]	...	1.7 ± 0.7
Active Region[g]	10956 beta	10982 beta	10998 HaP	11007 beta
Region location[g]	N03W50	S08W16	S10W26	N35W40
Nominal *ACE* high coronal connection[h]	W47	W39	W35	W59
Nearby large Coronal Hole?	N	N	Y	N
GOES X-ray flare peak flux[i]	B5	A1.1	...[j]	C1
X-ray flare peak time[i]	May 23 07:32	Feb. 4 13:35	...[j]	Nov. 4 03:17
ACE/EPAM or Wind/3DP electron event[k]	Y	N	N	Y
Type-III burst time[l]	May 23 07:17	...	...	Nov. 4 03:24
Preceding CIR?	N	Y	Y	N
Well observed CME?[m]	Y	N	N	Y
PFSS connect?	Y	Y	Y	N

Notes.
[a] Event discussed by Bučík et al. (2009).
[b] Event discussed by Wiedenbeck et al. (2009).
[c] Time intervals during magnetospheric upstream events were excluded from spectra and abundance calculation.
[d] Time intervals adjusted for velocity dispersion as described by Mason et al. (2000).
[e] Ion energy range 320–452 keV nucleon^{-1}; fluence units, particles (cm^{2} sr MeV/nucleon)$^{-1}$.
[f] Ratio not available at stated energy; result is approximate value from lower energy bin.
[g] NOAA/SWPC archive region daily locations at 00:00 were extrapolated to start time at rate of 13.2° day^{-1}.
[h] Extrapolated connection point using *ACE*/SWEPAM solar wind speed at start time.
[i] 1.0–8.0 Å GOES X-rays; letters denote flux decade: A: 10^{-8} W m^{-2}; B: 10^{-7} W m^{-2}; C: 10^{-6} W m^{-2}; e.g. B5 = 5×10^{-7} W m^{-2}.
[j] Brightening at June 16 06:05 observed by STEREO EUVI, but below GOES detection limit of $\sim 5 \times 10^{-9}$ W m^{-2}.
[k] *ACE*/EPAM energy: 38–53 keV; Wind/3DP energy range: ∼0.5–few hundred keV.
[l] NOAA/SWPC event reports; STEREO SWAVES and Wind WAVES; see text for discussion.
[m] SOHO CME catalog (http://cdaw.gsfc.nasa.gov/CME_list/index.html); also see text for discussion.

can be measured. Figure 2 shows event-averaged particle fluence spectra for the four events. The spectra for ^{4}He, O, and Fe are similar power laws, with index between −1.8 and −2.4 for ^{4}He. The ^{3}He spectrum is similar to ^{4}He in events 1 and 2; for events 3 and 4 the ^{3}He spectrum is distinctly flatter than ^{4}He, leading to a decrease in the ^{3}He/^{4}He ratio toward lower energies (e.g., see Mason et al. 2000, 2002). The somewhat broken spectral forms in panels (b) and (d) may be due to statistical fluctuations or temporary loss of magnetic connection to the particle source (e.g., Mason et al. 2000).

Figure 3 shows solar 195 Å images at the start time for each event. In each case there is a single region in the western hemisphere as a candidate source for the ion event. Figure 4 shows field lines calculated with the potential field source surface (PFSS) model (see Schrijver et al. 2003 and references therein). The model indicates that the solar active regions for events 1–3 had open field lines connecting to the ecliptic, while event 4 did not.

Table 1 shows that events 1 and 4 had energetic particle and type-III radio signatures typical of ^{3}He-rich events, as well as X-ray flares and CMEs associated with the particle injection. Events 2 and 3 are not typical and we discuss them next.

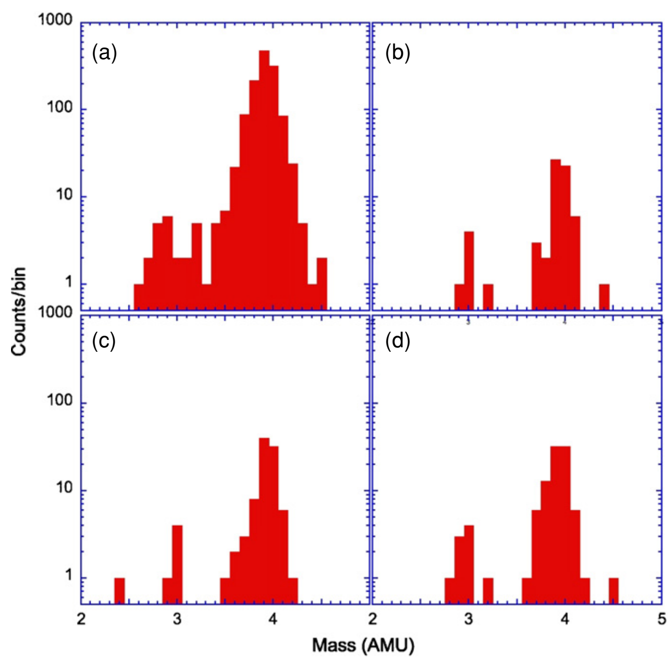

Figure 1. He mass histograms, (a)–(d) corresponding to events 1–4 in Table 1. Energy range is 0.225–2 MeV nucleon^{-1} for (a), 0.5–2 MeV nucleon^{-1} for (b)–(d).

2.1. 2008 February 4 Event

Event 2 took place during the decay of a CIR associated with a coronal hole at about W40–60° (Figure 3(b)). The solar wind speed was ∼600 km s^{-1} at the start of the period giving *ACE* a nominal connection point at ∼W39, not far from Active Region 10982. A western hemisphere CME was observed beginning February 5 05:30UT with a related type-III burst, about 30 hr after the start of the period. STEREO-B saw a much weaker

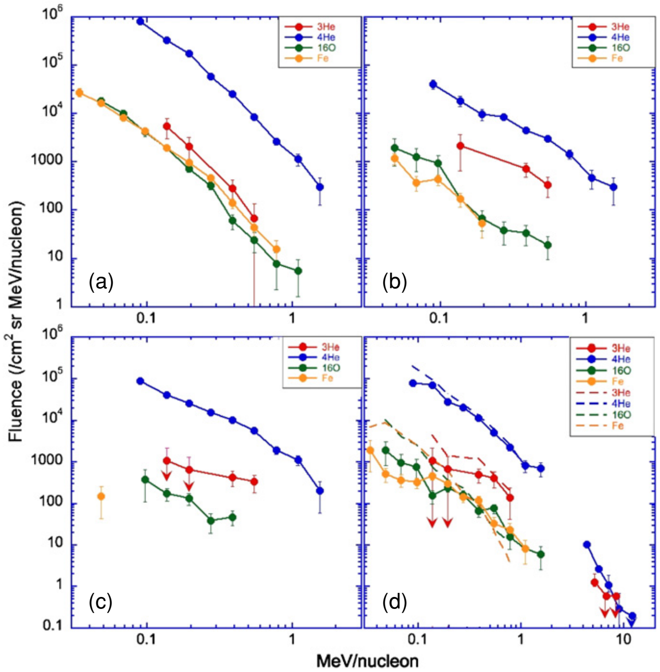

Figure 2. Fluences for events (a) 2007 May 23, (b) 2008 February 4, (c) 2008 June 16, and (d) 2008 November 4. Species are blue, ^{4}He; red, ^{3}He; green, O; orange, Fe. Dashed lines in (d) are discussed in the text. Note different energy scale in (d) to accommodate high energy points from *ACE*/SIS.

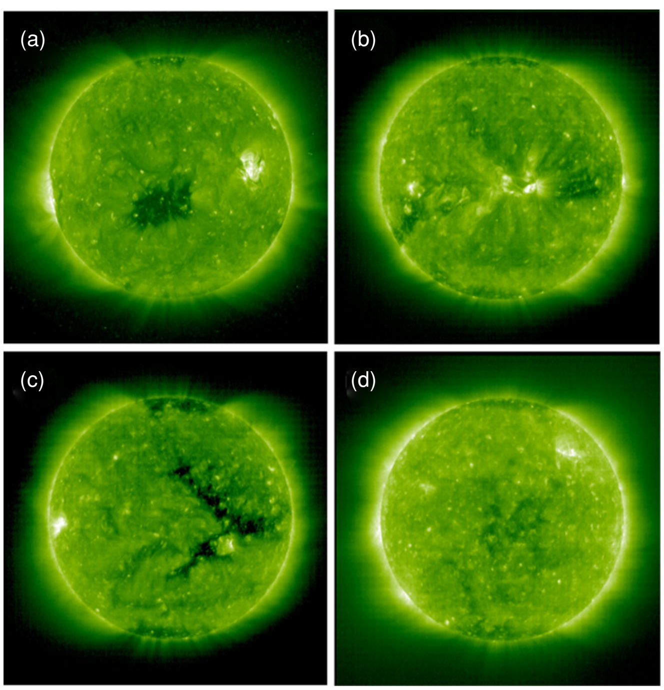

Figure 3. 195 Å solar images near start times in Table 1 for (a) 2007 May 23, (b) 2008 February 4, (c) 2008 June 16, and (d) 2008 November 4. Images from STEREO/SECCHI (a) and SOHO/EIT (b)–(d).

type-III than STEREO-A so we believe this activity was from a region ∼20° beyond the west limb from Earth, and not associated with the ^{3}He ion enhancement seen at *ACE*. *ACE* and Wind electron intensities remained close to the instrument background level; about 13.5 hr after the start of the period an A1 X-ray event occurred.

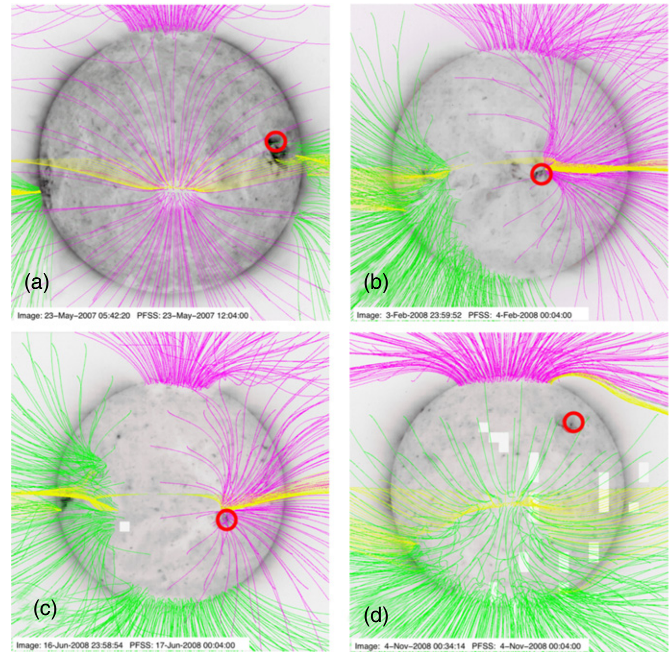

Figure 4. Open field line maps from photosphere to 2.5 $R_{\rm Sun}$ surface from the PFSS model. Green lines: positive polarities, pink lines: negative polarities; yellow lines: open field lines that connect to the ecliptic; red circles mark regions listed in Table 1. Panel dates are as in Figure 3.

2.2. 2008 June 16 Event

Event 3 took place during the decay of a CIR that began on June 15 in association with a nearby coronal hole (Figure 3(c)). On June 13, two days before the event, region 10998 was a simple bipolar active region; however, beginning June 14 00:00 the sunspots had decayed and it remained an H-α plage region without spots through the time it moved beyond the west limb on June 22. No X-ray flares are found in the GOES X-ray light curves during June 16–18, no radio bursts are included in the NOAA event report and there was no electron event seen at *ACE*/EPAM or Wind/3DP. However, there is a faint type-III burst visible in STEREO and Wind data around June 16 01:00UT, about 20 hr before the appearance of ^{3}He for this event. This type-III burst does not appear to be associated with the particle event since the propagation time to 1 AU for the ions is ∼5 hr, while the ion event started about 20 hr later. There are no CMEs reported on the SOHO site; however, there are several indistinct outflows coming from the west limb.

A notable feature of the particle fluences for event 3 is the lack of Fe above ∼100 keV nucleon^{-1}(Figure 2(c)). If Fe were ≈ O in this event, the Fe spectrum would lie near the O spectrum, and so would have been detected. It is possible that O spectrum is actually a remnant of the preceding CIR which overlaps this time interval, in which case a low intensity of Fe would not be surprising (Mason et al. 2009).

3. DISCUSSION

Periods of extended emission of energetic ^{3}He with no obvious injections have been reported during the *ACE* mission (Kocharov et al. 2008), as well as periods such as 11–14 December 2002 where there were several ^{3}He injections but these occurred in the midst of an extended period of ^{3}He emission (Wang et al. 2006). Events 2–4 reported here have similarities with these but took place near solar minimum conditions when there was much less activity at the Sun. For example, in event 4 the ^{3}He and ^{4}He spectra measured in the two-day period after the event (*dashed lines*, Figure 2(d)) are very similar to those during the event, even though there was only a single type-III and no CME or electron event.

^{3}He-rich SEPs have long been associated with solar active regions, and this association is extended in this work since the events observed occurred *only* when there was a candidate active region in the western hemisphere. The regions for events 2 and 3 were magnetically connected to the ecliptic according to PFSS calculations, strengthening the evidence for association (keeping in mind the limitations of the model). However, energetic electrons and type-III radio bursts, which are often associated with ^{3}He-rich SEPs, were not visible above instrument backgrounds in event 3, nor were X-ray flares, jets, or a clear CME. While these considerations do not negate these well established associations, they indicate that the ^{3}He emission apparently does not require these types of activity.

The lack of X-ray signatures implies that the acceleration may take place high in the corona above active regions (e.g., Lin 1993). However, this is not consistent with evidence for heavy-ion stripping in other ^{3}He-rich SEP events (e.g., DiFabio et al. 2008), nor with the nondetection of electrons in situ. Therefore these ^{3}He-rich events without X-ray signatures and electrons are puzzling. The observations here imply that some processes associated with active regions are capable of energizing the ^{3}He and heavy ions up to at least $\sim$1 MeV nucleon^{-1}.

We note that ^{3}He-rich SEP events often produce spectra extending to much higher energies than seen here, and with much greater intensities. In cases such as the 2002 December period mentioned above, these larger events are often associated with jets, CMEs, and other signatures of solar activity. It may be that these ejections provide the further energization of the initial population accelerated at or near the active region, and may also be responsible for the fact that the larger ^{3}He-rich SEP events tend to have spectral forms different from the smallest events (Mason et al. 2002).

We gratefully acknowledge the STEREO Science Center, SOHO CDAW data center, ACE Science Center, and NOAA/SWPC archives for data used in this study. We thank A. Vourlidas for comments on CME activity. This work was supported by NASA grants NNX07AP69G and NNG06GC21 at Johns Hopkins University/Applied Physics Laboratory, NASA Grant NNX8AI11G and NSF grant ATM-0454428 at the California Institute of Technology and the Jet Propulsion Laboratory, and NASA grants NNG05GD68G and NNX07AN13G at the Lockheed Martin Solar and Astrophysics Laboratory.

REFERENCES

Bučík, R., et al. 2009, Sol. Phys., in press
DiFabio, R., et al. 2008, ApJ, 687, 623
Drake, J. F., et al. 2006, Nature, 443, 553
Drake, J. F., Cassak, P. A., Shay, M. A., Swisdak, M., & Quataert, E. 2009, ApJ, 700, L16
Fisk, L. A. 1978, ApJ, 224, 1048
Kahler, S., et al. 1987, Sol. Phys., 107, 385
Kocharov, L., et al. 2008, ApJS, 176, 497
Kocharov, L. G., et al. 1984, Space Sci. Rev., 38, 89
Lin, R. P. 1993, Space Sci. Rev, 13, 265
Liu, S., et al. 2006, ApJ, 636, 462
Mason, G. M. 2007, Space Sci. Rev., 130, 231
Mason, G. M., et al. 1998, Space Sci. Rev., 86, 409
Mason, G. M., et al. 2000, ApJ, 545, L157
Mason, G. M., et al. 2002, ApJ, 574, 1039
Mason, G. M., et al. 2009, Sol. Phys., 256, 393
Miller, J. A., et al. 1996, ApJ, 461, 445
Nitta, N., et al. 2008, ApJ, 675, L125
Nitta, N. V., et al. 2006, ApJ, 650, 438
Pick, M., et al. 2006, ApJ, 648, 1247
Reames, D. V. 1999, Space Sci. Rev., 90, 413
Rust, D. M., et al. 2008, ApJ, 687, 635
Schrijver, C. J., et al. 2003, Sol. Phys., 212, 165
Wang, Y.-M., et al. 2006, ApJ, 639, 495
Wiedenbeck, M. E., et al. 2009, in Proc. 31st ICRC (Lodz), paper 1279
Zhang, T. X. 1999, ApJ, 518, 954