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Acceleration of ^{3}He nuclei at interplanetary shocks

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Abstract. We have surveyed the 0.5-2.0 MeV nucleon^{-1} ion composition of 56 interplanetary shocks (IP) observed with the Ultra-Low-Energy Isotope Spectrometer (ULEIS) on board the *Advanced Composition Explorer (ACE)* from 1997 October 1 through 2000 November 30. Our results show the first ever measurement (25 cases) of ^{3}He ions being accelerated at IP shocks. The ^{3}He/^{4}He ratio at the 25 shocks exhibited a wide range of values between 0.0014-0.24; the ratios were enhanced between factors of ~3-600 over the solar wind value. During the survey period, the occurrence probability of ^{3}He-rich shocks increased with rising solar activity as measured in terms of the daily occurrence rates of sunspots and X-ray flares. The ^{3}He enhancements at IP shocks cannot be attributed to rigidity dependent acceleration of solar wind ions and are better explained if the shocks accelerate ions from multiple sources, one being remnant impulsive solar flare material enriched in ^{3}He ions. Our results also indicate that the contribution of impulsive flares to the seed population for IP shocks varies from event to event, and that the interplanetary medium is being replenished with impulsive material more frequently during periods of increased solar activity.

1. Introduction

Enhancements in the intensities of energetic ions associated with transient interplanetary (IP) shocks have been observed routinely at 1 AU since the 1960's (e.g., Reames 1999). It is presently believed that the majority of such IP shocks are driven by fast coronal mass ejections or CMEs as they propagate through interplanetary space (e.g., Gosling 1993), and that the associated ion intensity enhancements are due to diffusive shock acceleration of solar wind ions (Lee 1983; Jones and Ellison 1991; Reames 1999). However, the putative solar wind origin of the IP-shock accelerated ions is based on composition measurements associated with a very limited number of individual IP shocks (Klecker et al. 1981; Hovestadt et al. 1982; Tan et al. 1989; Tylka et al. 1999). Although Klecker et al. (1981), Hovestadt et al. (1982), and Tan et al. (1989) interpreted their results in terms of shock acceleration of ions left over from prior solar energetic particle (SEP) events, the general consensus is that IP shock-accelerated ions originate from the solar wind (e.g., Reames 1999; Klecker et al. 2000).

Recently, however, in surveying energetic (~1 MeV nucleon^{-1}) ion measurements obtained during quiet periods in between the so-called large gradual SEPs observed at the *Advanced Composition Explorer (ACE)* spacecraft, Mason et al. (1999a) found that residual ^{3}He and Fe ions from impulsive SEPs or solar flares (e.g., Temerin and Roth 1992) can fill a substantial volume (>50%) of the in-ecliptic interplanetary medium during periods of high solar activity. Mason et al. (1999a) then suggested that such remnant impulsive material could be an important constituent of the seed population that is available for acceleration at coronal or IP shocks driven by CMEs. Thus, according to this hypothesis, IP shocks should accelerate ^{3}He ions provided that they encounter remnant flare material en route to 1 AU. The main goal of this paper is to search for ^{3}He ions accelerated locally at IP shocks observed at *ACE*. We discuss our findings in terms of characteristics of the source population that is available for acceleration at IP shocks and highlight new challenges for current ideas regarding the origin and acceleration of energetic particles at IP shocks.

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2. Observations and Data Analysis

We use energetic ion measurements in the 0.5-2.0 MeV nucleon^{-1} energy range obtained by the Ultra-Low-Energy Isotope Spectrometer (ULEIS, Mason et al. 1998) on board *ACE* which was launched in 1997 August. ULEIS identifies ions (H-Ni) in the ~0.02-10 MeV nucleon^{-1} energy range by making two time-of-flight (TOF) versus residual energy measurements for each ion, thereby enabling us to remove background events and identify ^{3}He ions unambiguously. This measurement technique, combined with a substantially large geometrical factor of ~1.3 cm^{2} sr, has essentially ensured that the resolution and sensitivity of ULEIS near ~1 MeV nucleon^{-1} greatly exceeds those of previous instruments. Thus, for the first time, we can compute the abundance of ^{3}He relative to ^{4}He not only during individual events but also when the corresponding abundance ratio is <0.1.

We started with a list of 95 CME-driven IP shocks that were observed at *ACE* between 1997 October 1 and 2000 November 30 (from www. bartol. udel. edu / ~chuck /ace /ACElists /obs_list.html). In order to restrict our search to ion populations accelerated locally at IP shocks near 1 AU, we have identified and eliminated all SEP events that were accelerated near the Sun e.g., impulsive solar flares. We identify the ion population accelerated at each IP shock by selecting the corresponding shock-associated time interval on the basis of the following: (1) The intensities of 0.5-2.0 MeV nucleon^{-1} ^{3}He, ^{4}He, O, and Fe nuclei should show enhancements of at least a factor of 5 within a 24-hour period centered on the arrival of the shock. (2) The intensity-time profiles of different species should track each other, indicating a common acceleration and transport history for all species. (3) The associated Fe-group ions in the 0.03-3.0 MeV nucleon^{-1} energy range should not exhibit velocity dispersion during onsets, indicating that the ions originate from the vicinity of the spacecraft.

Figure 1 displays the measurements of ULEIS from 2000 October 10 through 2000 October 15. Figure 1a shows that the intensities of 0.5-2.0 MeV nucleon^{-1} ^{3}He, ^{4}He, O, and Fe nuclei start increasing from ≈0530 UT on 2000 October 11, i.e., ≈41 hours prior to the arrival of the IP shock (marked S) at ACE at 2145 UT on 2000 October 12. The peak at the shock is followed by a larger peak at ~0200 UT on 2000 October 13. The intensities then decrease by more than an order of magnitude until ~1900 UT on 2000 October 13. Since the intensities of different species peak near the shock and track each other within a factor of 2 from ~0530 UT on 2000 October 11 till ~1900 UT on 2000 October 13, we conclude that the ions detected during this 62-hour interval (indicated by the vertical dashed lines) have a common acceleration and propagation history, with the acceleration process occurring at the IP shock.

Figure 1b displays the energy spectrogram of 0.03-3.0 MeV nucleon^{-1} Fe-group ions and emphasizes one of the key differences between the SEPs accelerated near the Sun and the IP shock-accelerated ions. Owing to propagation effects the ions accelerated near the Sun exhibit normal velocity dispersion during onsets wherein the faster ions arrive earlier than the slower ions. This behavior may be easily identified from energy spectrograms like Figure 1b (see e.g., Mazur et al. 2000) because it is markedly different from that of the IP shock-accelerated ions which originate from the vicinity of the spacecraft and arrive nearly simultaneously. For instance, Figure 1b shows that the Fe-group ions exhibit no velocity dispersion from ≈0530 UT on 2000 October 11 till ≈1900 UT on 2000 October 13, as expected for locally accelerated ion populations.

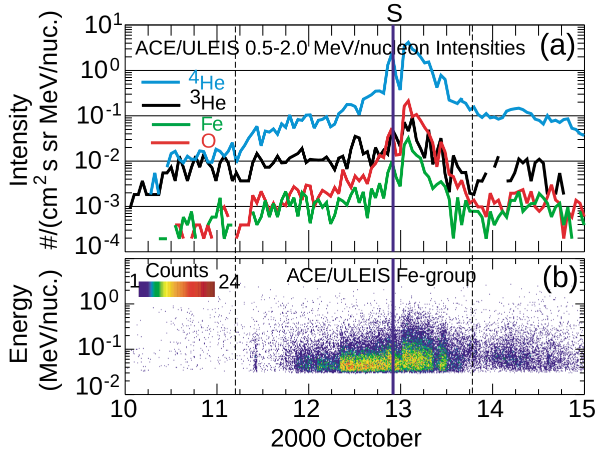

Fig 1: (a) Intensity-time profiles of 0.5-2.0 MeV nucleon^{-1} ^{3}He, ^{4}He, O, and Fe nuclei, and (b) energy spectrogram of 0.03-3.0 MeV nucleon^{-1} Fe-group ions measured by ULEIS from 2000 October 10 through 2000 October 15. The solid vertical line, marked S, at 2145 UT on 2000 October 12 shows the arrival of the interplanetary shock at ACE. Dashed vertical lines identify the time intervals during which ULEIS measured energetic ions associated with the shock.

In our survey, 21 of the 95 shocks occurred during complex time periods and we could not distinguish the local IP shock-accelerated ions from the SEPs accelerated near the Sun. For instance, the period 1997 November 4-November 10 contained two IP shock events as well as SEPs accelerated near the Sun (e.g., Mason et al. 1999b); such events are excluded from the analysis. 18 of the remaining 74 shocks were not associated with local enhancements in the intensities of ~1 MeV nucleon^{-1} ions and are not included in the survey. Of the remaining 56 events, we found 30 events with < 10 ^{3}He counts, i.e., ions in the 2.8-3.2 AMU mass range, and 1 event with sufficiently high background that the corresponding mass peak for ^{3}He was neither well resolved nor finite.

The mass peaks for ^{3}He during the remaining 25 events in our survey were finite and well resolved. Figures 2a-2f display the 0.5-2.0 MeV nucleon^{-1} mass histograms for 6 of these events. The excellent mass resolution of ULEIS along with the low background during the events is clearly

Table 1: List of IP shocks with high[a] ^{3}He/^{4}He ratios

No.	Shock Time[b]	Start Time[b]	Stop Time[b]	No. of ^{3}He counts	^{3}He/^{4}He ratio
	1998				
1…	Jan. 28, 1600	Jan. 27, 0000	Jan. 30, 0000	55	0.0437 ± 0.0061
	1999				
2…	Sep. 15, 1938	Sep. 15, 1519	Sep. 16, 2240	42	0.1585 ± 0.0263
	2000				
3…	Jan. 22, 0023	Jan. 20, 1040	Jan. 24, 1120	50	0.0418 ± 0.0060
4…	Apr. 24, 0850	Apr. 23, 0657	Apr. 24, 1755	507	0.2402 ± 0.0119
5…	July 11, 1124	July 11, 0204	July 12, 0555	145	0.0430 ± 0.0037
6…	Oct. 12, 2145	Oct. 11, 0537	Oct. 13, 1906	222	0.0494 ± 0.0035

[a]shocks with ^{3}He/^{4}He ratio more than a factor of 100 over the solar wind value
[b]all times are in UT, as defined in text

evident from the finite and well-resolved peaks for ^{3}He and ^{4}He. We calculate the ^{3}He/^{4}He ratio during each event by dividing the number of counts detected in the 2.8-3.2 AMU mass range for ^{3}He by those detected in the 3.5-4.5 AMU mass range for ^{4}He. The number of ^{3}He counts is determined after subtracting possible contributions to the ^{3}He mass peak from spill-over from the more abundant ^{4}He and the background, which are respectively indicated by solid curves and dashed lines in Figure 2.

The ^{3}He/^{4}He ratio during the 25 events varies between 0.0014 ± 0.0005 and 0.2402 ± 0.0119. We refer to these events as ^{3}He-enriched shock events because the ^{3}He/^{4}He ratio is enhanced between factors of ~3-600 over the corresponding ratio (~0.000408 ± 0.000025 from Gloeckler and Geiss 1998) measured typically in the slow solar wind. Our survey shows that the ^{3}He abundance relative to ^{4}He was >0.1 during 2 events, was between 0.01-0.1 during 11 events, and was between 0.001-0.01 during 12 events. Table 1 lists the 6 shock events for which the ^{3}He/^{4}He ratio was >0.04, i.e., events for which the ^{3}He/^{4}He ratio was enhanced by more than a factor of 100 over the solar wind value. The event described in Figure 1 corresponds to event 6 in the Table and the 0.5-2.0 MeV nucleon^{-1} mass histograms for these 6 events are shown in Figures 2a-f. The table also lists the shock-associated time interval, the number of ^{3}He counts, and the ^{3}He/^{4}He ratio for each event.

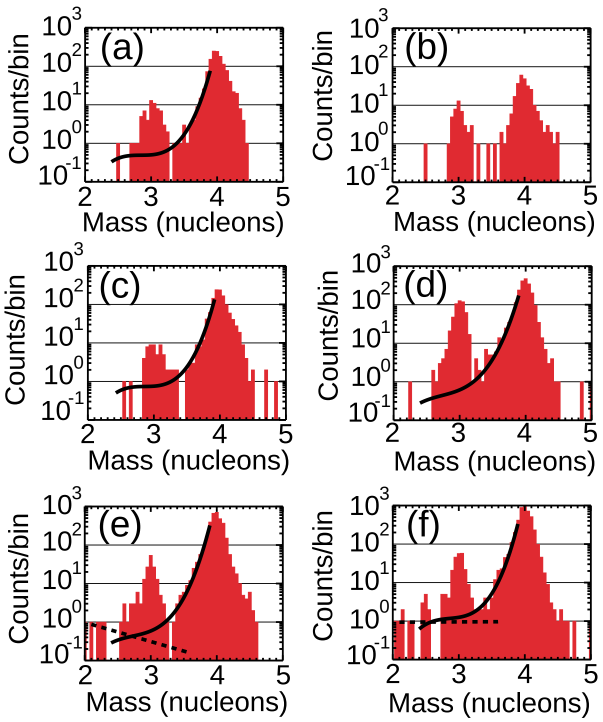

Fig 2: The 0.5-2.0 MeV nucleon^{-1} mass histograms for the 6 ^{3}He-enriched IP-shock events listed in Table 1. The solid curves and dashed lines are used to estimate contributions of spill-over from ^{4}He and the background, respectively, to the ^{3}He mass peaks.

To investigate the occurrence probability of the ^{3}He-rich shocks, we have divided the data set into two nineteen month periods, namely, (1) Period A: 1997 October 1 till 1999 April 30, and (2) Period B: 1999 May 1 till 2000 November 30. Table 2 provides a comparison between the incidence probabilities of the ^{3}He-rich shocks and the solar activity levels during these periods. The occurrence rate of ^{3}He-rich shocks increases by about a factor of 5 during period B when compared with that observed during period A. This also coincides with an increase in solar activity during Period B, as evident from the factor of 2 enhancement in the daily occurrence rates of both, sunspots and X-ray flares (obtained from gopher://solar.sec.noaa. gov:70/).

3. Discussion

We have measured the ^{3}He/^{4}He abundance ratio during 56 CME-driven IP shock events observed at ACE. Our results are: (1) The mass peaks for ^{3}He during 25 shock events are finite and well resolved; the ^{3}He/^{4}He ratio during these events exhibited a wide range of values between 0.0014-0.24. (2) The ^{3}He/^{4}He ratio was enhanced between factors

Table 2: Occurrence probability of ^{3}He-rich IP shocks

Characteristics	Period A	Period B
Dates………………………………………………	1997 October 1 -1999 April 30	1999 May 1 -2000 November 30
No. of CME-driven shocks…………………………	41	54
No. of shocks with accelerated ion populations…..	21	35
No. of ^{3}He-rich shock events[a]………………………	3	22
Occurrence probability of ^{3}He-rich shocks……….	0.14 ± 0.09	0.63 ± 0.17
No. of sunspots/day[b]………………………………..	86.56	172.3
No. of X-ray flares/day[b]……………………………	3.57	6.64

[a]only includes shocks with >10 ^{3}He counts
[b]obtained from gopher://solar.sec.noaa.gov:70/

of ~3-600 over the corresponding solar wind value; during 6 events, the ^{3}He/^{4}He ratio was enhanced by more than a factor of 100 over the solar wind value. (3) The occurrence probability of ^{3}He-rich shocks, and the occurrence rates of X-ray flares and sunspots increased dramatically during the nineteen month period starting from 1999 May 1 when compared with the preceding nineteen month period starting from 1997 October 1.

The two possible explanations that could account for the above results are: (1) the ions originate from a single source such as the solar wind and are accelerated via a rigidity dependent acceleration process (Lee 1983; Jones and Ellison 1991; Tylka et al. 1999; Klecker et al. 2000), or (2) the ions originate from a combination of two or more source populations, one being remnant impulsive SEP material that is enriched in ^{3}He ions (Mason et al. 1999a; 1999b), the other presumably being the suprathermal tail of the solar wind.

The first explanation may be ruled out for three reasons. First, the ^{3}He/^{4}He ratio in the solar wind lies in the range 0.00029-0.00044 (from Gloeckler and Geiss 1998), whereas the ^{3}He/^{4}He ratios at IP shocks exhibit a wide range of values encompassing more than two orders of magnitude; such widely varying enhancements cannot be attributed to shock acceleration of solar wind ions. Second, we note that although rigidity dependent acceleration of solar wind material could produce modest (up to factors of ~10) enhancements (Klecker et al. 1981; 2000), the fact that the ^{3}He/^{4}He ratio during the 6 events listed in Table 1 is enhanced by more than a factor of 100 over the solar wind value cannot be reconciled with the hypothesis that these shocks accelerate ions directly and exclusively out of the solar wind. Third, if the IP shocks were accelerating ions exclusively out of the solar wind, then we would have expected the occurrence probability of the ^{3}He-rich shocks to be independent of solar activity, which is also inconsistent with the results presented here.

In contrast, our results may be easily explained if the seed population available for acceleration at IP shocks comprises ions from multiple sources, one for certain being remnant impulsive SEP material enriched in ^{3}He ions, as suggested by Mason et al. (1999a). Further, the fact that the occurrence probability of the ^{3}He-rich shocks increases with rising solar activity and is >50% between 1999 May 1 and 2000 November 30 is consistent with the observation of Mason et al. (1999a) i.e., that remnant flare material can fill >50% of the interplanetary medium during periods of high solar activity. In addition, the large variability in the ^{3}He/^{4}He ratio indicates that there is a dramatic difference in the amount of impulsive SEP material that is available for further acceleration from event to event. Since the majority of the ^{3}He-rich shocks were observed when the Sun was more active, we conclude that the interplanetary medium inside ~1 AU is being replenished with impulsive material more frequently during periods of high solar activity. Important implications of these results for shock acceleration theories are discussed in Desai et al. (2001).

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