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Spectral forms in ^{3}He-rich solar particle events

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Abstract

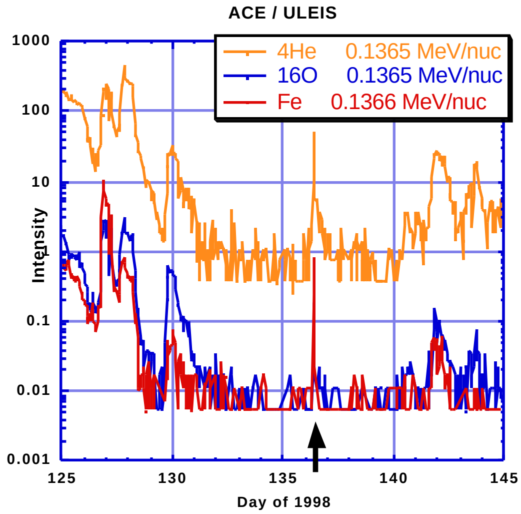
With the increase of solar activity accompanying the current rise to solar maximum, the number of ^{3}He-rich solar energetic particle (SEP) events has increased dramatically compared to the quiet 1992-1997 period. Using the Ultra-Low-Energy Isotope Spectrometer (ULEIS) on ACE, we have observed large numbers of events enriched in ^{3}He. The high mass resolution and large energy range of ULEIS (0.1 - 5 MeV/nucleon) makes it possible to study hitherto unobservable aspects of the energy spectra and abundances in these events. We find that in some events the ^{3}He spectral form is significantly different from ^{4}He, and that the heavy ion spectra are generally similar. These features may provide important new clues and constraints for theories for the acceleration process.

1 Introduction:

Solar particle events enriched in ^{3}He have received intensive study since they appear to be the result of acceleration processes on the Sun that are distinctly different from those that produce the largest solar flares (e.g., Kocharov & Kocharov 1984 and Reames et al. 1994, and references therein). Because these events are relatively small, spectral forms are difficult to investigate. Möbius et al. (1980; 1982) reported an increase in the ^{3}He/^{4}He ratio with increasing energy between 0.44 and 4.1 MeV/nucleon for 14 events during 1974-79; for 6 of the events, the O spectrum was somewhat harder than the Fe spectrum over the same energy range. Mazur et al. (1995) examined heavy ions spectra in 11 events during the 1992-94 period with high sensitivity instruments, and found that the spectra routinely extended up to ~16 MeV/nucleon. In most of the cases, the Fe spectra were well fitted by power laws, although in two there was a rollover towards lower energies similar the spectra reported by Möbius over a narrower energy range. In the Mazur et al. study, the spectra slopes of He and the heavy ions were similar. Reames et al. (1997) used Wind instruments to probe spectra down to 0.1 MeV/nucleon, finding power law forms in most cases, and also finding an increase in the ^{3}He/^{4}He ratio in 2 out of 6 cases. In this study, we use the ULEIS instrument (Mason et al. 1998) on ACE to further explore spectra in such events over a broader energy range than in previous work.

2 Observations:

Although ^{3}He-rich events have been observed during the recent solar minimum, the rate of events increased markedly around 1998 day ~90. Most previous surveys of ^{3}He-rich events have placed a cutoff threshold of ^{3}He/^{4}He ~0.1; the very high mass resolution of ULEIS allows us to explore much lower ratios, which nevertheless represent large enhancements over the typical solar wind ^{3}He/^{4}He ratio of 5×10^{-4}. Over the ~18 month length of the survey, we have observed >60 periods where Fe and/or ^{3}He are enriched; many of these periods contain multiple, overlapping injections. There is an extremely rich variety of events in the survey: most are small, but a few are characterized by sizable increases in >10 MeV protons. Here we describe three events that illustrate some of the range of properties. All observations reported here were taken when ACE was



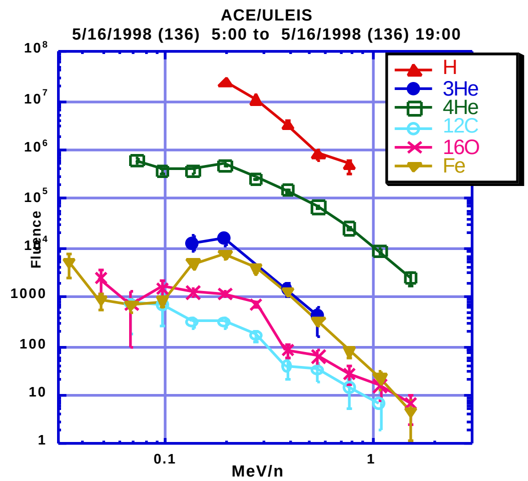


Figure 1: particle intensities (/sec-cm^2 sr MeV/nucleon) for 1998 days 125-145

Figure 2: fluences (/cm^2 sr MeV/nucleon) during spike-like event on day 136.

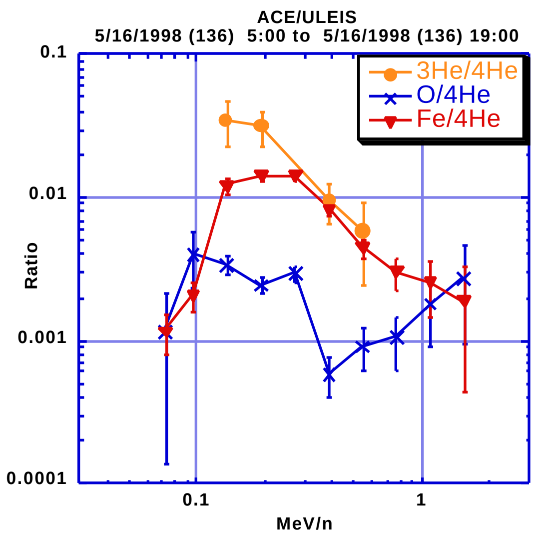


Figure 3: ^{3}He/^{4}He, O/^{4}He, and Fe/^{4}He ratios

near the L1 Lagrangian point, far upstream of Earth.

Figure 1 shows 0.135 MeV/nucleon ^{4}He, ^{16}O and Fe intensities for a 20 day period beginning 1998 day 125. Note the numerous intensity increases including some in which Fe exceeds O (e.g., day 126). The arrow in the figure points to a spike-like event on day 136 that featured relatively large intensities of He, O and Fe. The onset of this event showed no velocity dispersion. However, at this initial time, there was no intensity increase observed below ~200 keV/n; then, these and lower energy particles began to appear showing normal velocity dispersion. We interpret this as indicating that at the onset the spacecraft entered a magnetic region that had already been filled by particles more energetic than ~200 keV/n, and then these lower energy particles arrived in the normal fashion (Mazur et al. 1999). The low energy intensity increases ended abruptly after a few hours, again showing no velocity dispersion -- indicating that the spacecraft had moved out of the magnetic region. Figure 2 shows particle *fluences* for this period, showing a distinct maximum near ~150-200 keV/nucleon; since this maximum was caused by propagation effects it is not a true measure of the spectrum at the flare site. Notice the huge Fe/O ratio. Figure 3 shows ratios for ^{3}He/^{4}He, O/He, and Fe/^{4}He: notice that the ^{3}He/^{4}He ratio *decreases* from a few percent around 100 keV/n to <1% above 0.5 MeV/nucleon. The O/^{4}He and Fe/^{4}He show no systematic trend with energy; O/^{4}He is lower than

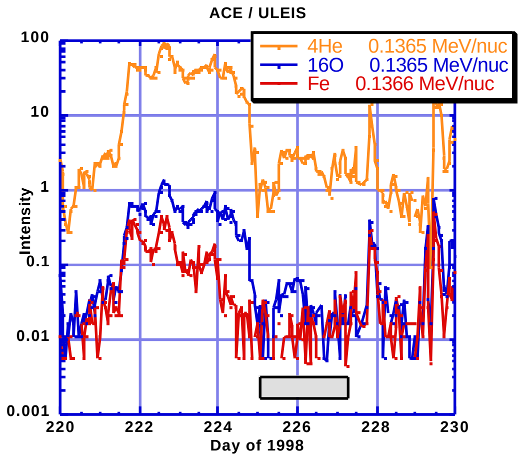


Figure 4: 0.135 MeV/nuc intensities for 1998 days 220-230; hatched box marks averaging interval.

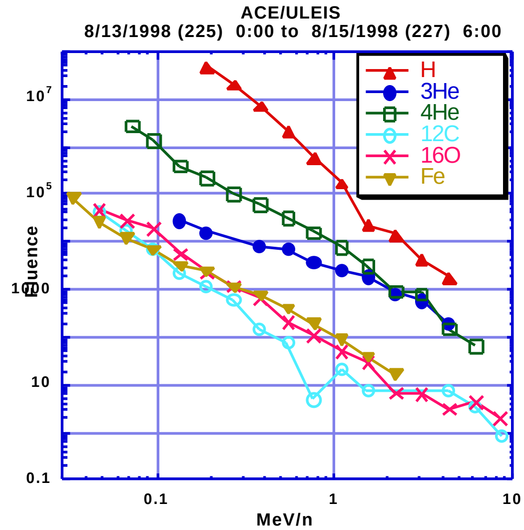


Figure 5: fluences for 1998/225-227

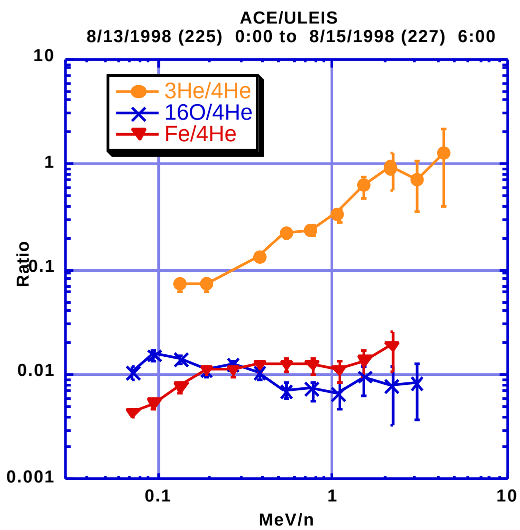


Figure 6: ratios during event

typical values in large solar particle events, while the Fe/^{4}He is comparable to that in large SEP events.

Figure 4 shows an example of an event that lasted for >2 days, in contrast with the spike-like event discussed above. The time interval here was chosen because a clear increase in ^{3}He was seen at higher energies by the SIS instrument on ACE (Wiedenbeck et al. 1998). For the low energy particles shown in Figure 4, notice that the Fe increase occurs later than the ^{4}He and O. Spectral forms for the period are shown in Figure 5, and ratios of key elements are shown in Figure 6. Notice the dramatic increase of ^{3}He/^{4}He by over an order of magnitude, while the ^{4}He, O, and Fe spectra are similar in shape from <0.1 to several MeV/nucleon. The O/He spectra are very similar, while the Fe spectrum is somewhat harder than the O.

Figure 7 shows intensities for the third example, during January 1999. In this case there was modest solar activity beginning on Jan. 4, with complex temporal variations. During this period, the Fe/O ratio was close to large SEP values, and ^{3}He abundances were at <few percent. Then on Jan. 6, there was a distinct injection of ^{3}He (black trace in Figure 7), whose intensities rose by over a factor of 100; the ^{4}He, O, and Fe intensity increases were more modest, presumably because of the prior elevated intensity levels. Figure 8 shows the energy spectra measured during the period denoted by the hatched box in Figure 7: the selected period begins with the ^{3}He injection and continues through the decay of the event. In this case, the ^{3}He/^{4}He ratio is ~1, and the Fe/O also ~1. The ratios of the intensities shown in Figure 9 show little energy dependence for O/^{4}He and Fe/^{4}He. The ^{3}He/^{4}He ratio appears to show a peak at a few hundred keV/nucleon, but this should be confirmed with higher energy observations.

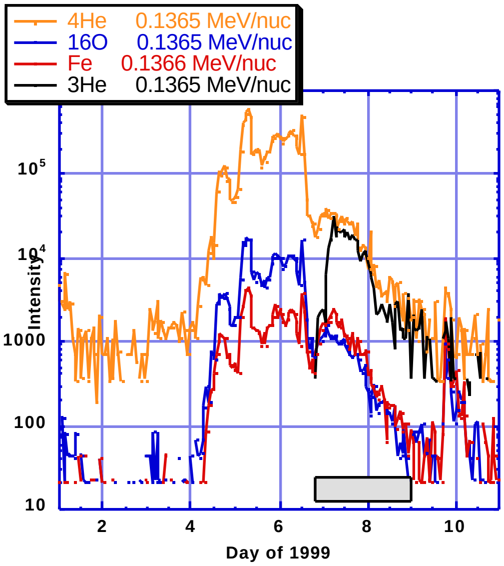


Figure 7: intensities during 1999 days 1-11

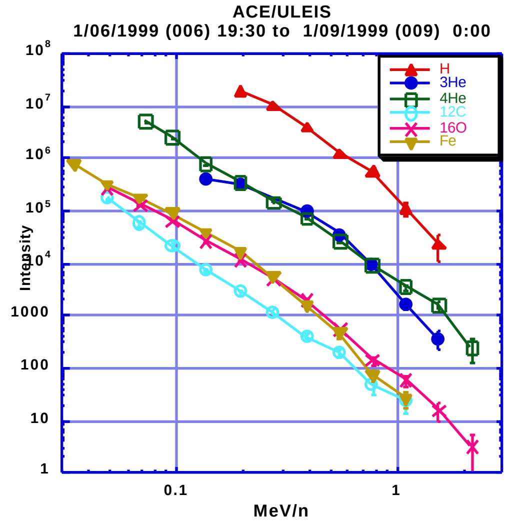


Figure 8: fluences during time interval marked by hatched box in Figure 7

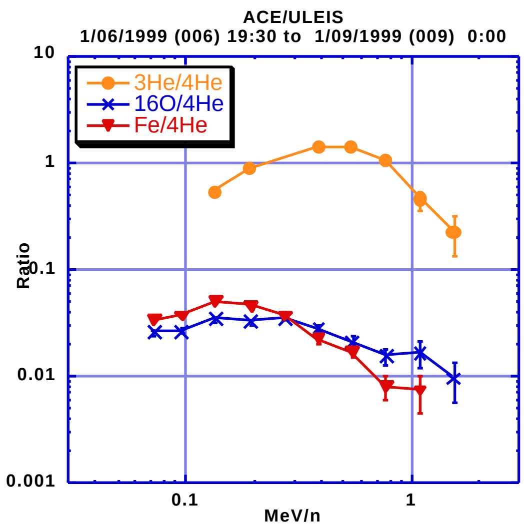


Figure 9: ratios of spectra in Fig. 8

3 Discussion:

The three events discussed here illustrate a variety of properties that challenge theories and models for these events. For example, models that achieve enrichment of ^{3}He through resonant plasma wave heating (e.g. Fisk 1978) with final acceleration by a second-stage mechanism would generally be expected to produce similar ion spectra such as those seen in the 1999 days 6-9 period. However, events such as 1998/225-227 with ^{3}He spectra different from all the others do not seem to fit easily into this picture. The spectra reported here are generally close to power laws, without roll-overs at low energies such as reported by Möbius et al. Finally, there are events such as 1998 day 136, that contain huge Fe enrichments, and little ^{3}He compared to the others. Other mechanisms (e.g. Miller 1998) might better predict some of the features described here, but it is not clear that they can explain the full variation in observed properties.

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