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Heavy Elements in Solar Particle Events During the Solar Cycle 23: SOHO/ERNE Measurements

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During its operational time ERNE particle instrument (the Energetic and Relativistic Nuclei and Electron Experiment) onboard Solar Heliospheric Observatory (SOHO) has measured several large gradual solar particle events in the energy range from a few MeV/nucleon to few hundreds of MeV/nucleon. These particles are thought to be accelerated in shocks driven by fast coronal mass ejections (CMEs) and by studying these events, we can increase our knowledge about shock acceleration and particle transport. The heavy particles ($Z \geq 2$) are very useful in this regard. Elemental and isotopic ratios can help us to identify specific seed populations, and the particle species with suitable charge-to-mass (Q/A) ratios provide us with information about the various effects that govern particle injection, acceleration and transport. We present our results from the survey, in which we identified large particle events that occurred between May 1996 and June 2003, and observed several key parameters of these events. Whenever it was possible, we studied the time development of a few elemental ratios (especially Fe/O). The survey was partly motivated by an effort to create an extensive list of SEP events measured by ERNE (to be published on our website, http://www.srl.utu.fi/erne_data/). Our survey found 41 events observed during the selected time period, but only 22 events were included into the first phase of the study. The results presented here are preliminary.

1. Introduction

The Energetic and Relativistic Nuclei and Electron Experiment (ERNE) began its observations just before the beginning of the Solar Cycle 23. During the years of cycle 23 we have seen some spectacular events like "Bastille Day" event in July 2000, the "Halloween" events in October-November 2003, or the event of January 2005. These and all other large gradual events are thought to be accelerated by CME driven shocks, but details of acceleration mechanism or seed populations are not yet fully understood. The variability of the elemental composition among large SEP events is a problem; even events with similar solar progenitors can show huge variations in elemental ratios (e.g. Fe/O) with energies > ~10 MeV/nucleon [1]. One of the other problems is the events with composition matching the composition expected on average for impulsive events [1~3]. Tylka et al. have suggested an explanation involving a perpendicular shock [1]. To find explanations to these and other problems related to shock acceleration and particle transport, we must study not only individual events, but also perform statistical studies on large number of events.

In the first phase of our survey, we have identified the large gradual SEP events measured by ERNE and observed several key parameters of these events (for all events: H/He fluence, power-law fits for O and Fe, Fe/O). For some of the events, it was also possible to study the time development of few elemental ratios. This phase was partly motivated by an effort to create an extensive list of SEP events measured by ERNE (to be published on our website, http://www.srl.utu.fi/erne_data/). Similar lists for other instruments are available (e.g. [1, 4]).

The ERNE instrument consists of two sensors, the Low Energy Detector (LED) and the High Energy Detector (HED). LED has a total geometric factor of 0.9 cm^2sr and the energy coverage varies dependent on the particle species from 1.3 MeV/nucleon to ~30 MeV/nucleon. The geometric factor of HED varies with energy from 25 to 40 cm^{2}sr. HED extends the energy range of ERNE from LED energies up to few hundreds of MeV/nucleon. The positioning of the both detectors is such that the detectors are looking constantly into the direction of the average interplanetary magnetic field (IMF) line. This allows accurate anisotropy measurements of particle fluxes with its large field of view (120°). For more information, see [5].

2. Observations

ERNE gives an excellent opportunity to study SEP events that have occurred during the Solar Cycle 23, because both of ERNE's particle telescopes have remained operational throughout the cycle and operations will hopefully continue to the end of the SOHO mission. There's only one large gap in the data, the ~3 month period on summer-autumn of 1998, when SOHO was almost lost in space. Our survey period began from May 1996, but due to the solar minimum, first large gradual SEP event accepted into our list occurred over a year later on November 1997. We ended our survey to June 2003 and at that point we had 41 events in our list (but only 22 events were included into the first phase of study). To identify SEP event for the list, we examined both protons and a few most abundant heavier ions in the energy range from ~30 MeV/nucleon to ~100 MeV/nucleon.

The results from our survey will be discussed in detail in an upcoming paper, so we have limited the scope of this paper to one event. The event which we selected as an example occurred on April 15, 2001. It was associated with a X14.4 flare (S20°W85°) and the CME speed was 1200 km/s [3] and the onset time was 14:30 UT. There was a preceding event on April 14 (M1.0, S16°W71°, 830 km/s). Figure 1 shows event-averaged O and Fe spectra with a standard power-law fit to measurements between 8 and 300 MeV/nucleon. The Fe has a significantly harder power-law index than oxygen and this causes Fe/O to reach impulsive values at higher energies in figure 3. The fit between LED and HED is excellent for O, but Fe calibration clearly needs to be improved. The drop in Fe intensity between 5 - 7 MeV/nucleon is caused by an instrumental effect (the transition between two detector types that LED uses).

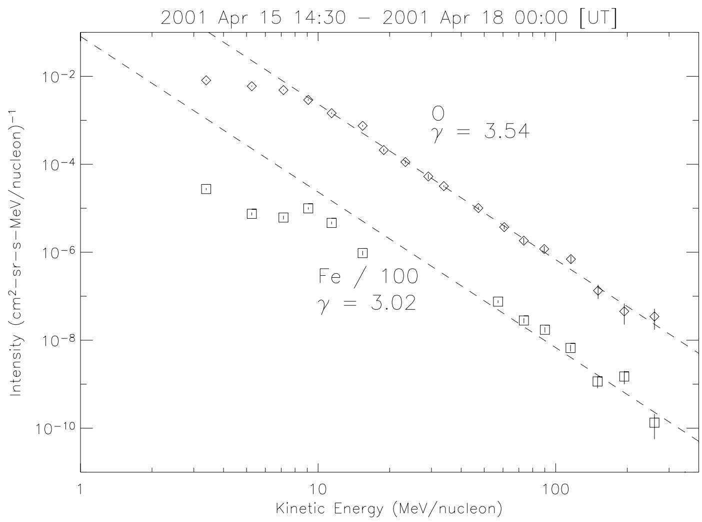

Figure 1. Event-averaged O (diamonds) and Fe (squares, divided by 100) spectra of the 2001 Apr 15 event. Both LED and HED data was used (9 first data points for O and 6 first points for Fe are from LED). The LED data used was partially uncalibrated. Power-law fits to data present energy range 8 – 300 MeV/nucleon (although there is an intensity difference with LED Fe and HED Fe, given power-law index is valid for both).

Figure 2 illustrates the time-intensity profiles of the April 15 event. At lower energies the ordering of O and Fe is clear throughout the event and resulting Fe/O is enhanced but quite independent of time (figure 3). At HED energies, Fe and O are comparable only at the beginning of the event. The Fe/O drops from the initially 'impulsive' values to more normal enhanced value, but on the last day of the event, there's a big jump in the Fe/O. This is probably caused by a flatter decay time profile for Fe.

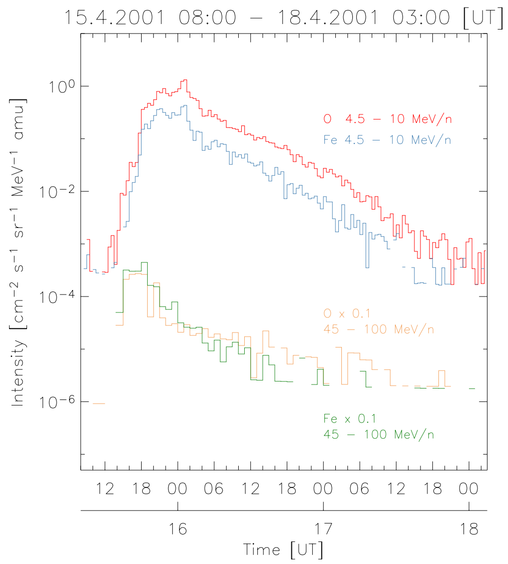

Figure 2. Time-intensity profiles of April 15, 2001 event. At the top is 4.5-10 MeV/nucleon energy channel for O (red), below is Fe with the same energy channel (blue). For the 45-100 MeV/nucleon energy channel, O and Fe are overlapping. At the beginning Fe intensities (green) are higher, but towards the end of the event, O intensities (orange) rise over Fe. Both O and Fe are multiplied with 0.1 to avoid overlap with LED time profiles.

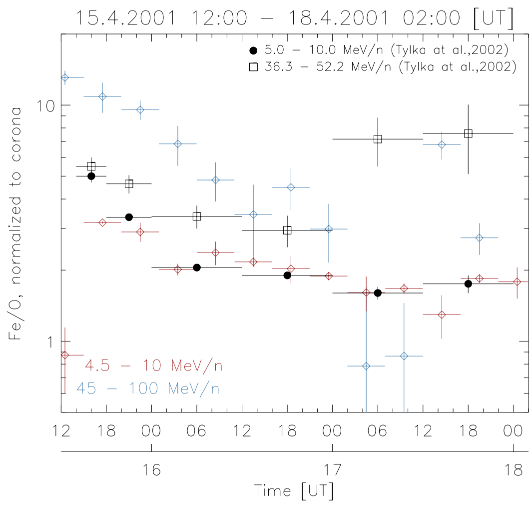

Figure 3. The time dependency of Fe/O (normalized to coronal value of 0.134 [6]). Black closed circles and open squares are from [3], red open circles are for energy channel 4.5 – 10 MeV/nucleon, blue open circles are for energy channel 45 – 100 MeV/nucleon.

3. Summary

Our survey found that 41 large gradual events were measured by ERNE during the time period from May 1996 to June 2003. 22 of these events were included into first phase of our study. H/He fluences were used to estimate event sizes. The power-law indexes were calculated for each event with energies 3.5 – 11 MeV/nucleon and ~30 – 100 MeV/nucleon; 20 of 22 events in our study had steepening oxygen spectra (Fe: 19/22). Event-averaged Fe/O ratios were calculated for each event; for the events with sufficient amounts of Fe, we were also able to study the time development of the Fe/O ratio.

The online database is under construction and it will be made available as soon as possible. In the future, we are going to extend the time span of our study from May 1996 to present. This will increase the number of events in the database to ~50. The database will be available on our website, http://www.srl.utu.fi/erne_data/.

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